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A UNIQUE SWITCHING DEVICE FOR INDUCTIVE ENERGY STORAGE SYSTEMS

H. K. Smithson and Jack D. Whitfield

ARO, Inc.

September 1966

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A UNIQUE SWITCHING DEVICES FOR INDUCTIVE ENERGY --
STORAGE SYSTEMS

3. Inductive energy
4 Gun switches

15-4.

H. K. Smithson and Jack D. Whitfield
ARO, Inc.

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for ODC-TAB-72-6, 15 Apr. 72

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FOREWORD

The research reported herein was done at the request of Headquarters, Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee under System 921C, Project 9106.

The results of research reported herein were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, under Contract AF40(600)-1200. The research was conducted from October 28, 1964 through April 11, 1966 under ARO Project No. VT1509, and the manuscript was submitted for publication on July 20, 1966.

The authors would like to thank the many people who participated in this development program. In particular, the authors wish to acknowledge the contributions of the late Mr. James R. Dearman and Mr. William Otto of the Army Missile Command who influenced the program by many helpful suggestions and stimulating discussions.

This technical report has been reviewed and is approved.

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ABSTRACT

The Arnold Engineering Development Center, von Kármán Gas Dynamics Facility and the Army Missile Command have engaged in a cooperative effort to develop an efficient current interrupting device to be used with inductive power supplies. A unique switch, termed the "gun switch", has been developed which utilizes gunpowder as a propellant to drive a plastic piston into, and shear, an electrical ribbon conductor. The gun switch has transferred up to 220,000 joules (36,000 amp) into an 0.06-ohm, 6- μ h load with an electrical transfer efficiency of 97 percent.

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NOMENCLATURE

E	Energy, joules
i	Current, amp
\bar{k}	Average dv_g/dt , v/sec
L	Inductance, h

p	Pressure
R	Resistance, ohms
t	Time, sec
v	Voltage, v
η	Efficiency, percent, $(1 - E_s/E_o) \times 100$

SUBSCRIPTS

a	Master gap arc-over conditions
c	Combustion chamber
L	Load conditions
o	Initial conditions at $t = 0$
s	Switch (or fuse) conditions

SECTION I INTRODUCTION

The feasibility of using an inductive energy storage system to drive an array of high impedance flash tubes which, in turn, excited a high energy laser array was demonstrated by Walker and Smithson (Ref. 1). This work was conducted by a joint cooperative effort between the Arnold Engineering Development Center*, von Kármán Gas Dynamics Facility (AEDC-VKF) and the Army Missile Command (AMICOM).

Special switching techniques are required to transfer a high energy pulse from the inductive storage loop into the high impedance flash tube load. Walker and Smithson (Ref. 1) describe the development of a so-called "copper tube" fuse capable of transferring $\approx 0.6 \times 10^6$ joules; however, as they point out, approximately an equal amount of energy was consumed in the fuse (i. e. switch) device. Dow, Lawrence, and Rozian (Ref. 2) have also conducted research on high current fusing techniques for inductive power supplies, and Baxter (Ref. 3) discusses related problems. Apparently, from the previous research (Refs. 1 and 2) and the known literature, highly efficient switching techniques for high impedance loads on an inductance energy storage system are not available.

Since the unit energy cost of a relatively large ($> 10^6$ -joule) inductance energy storage system is appreciably less than for a comparable capacitance energy storage system (Ref. 4), the desire to develop efficient switching techniques for inductive power supplies is of considerable practical concern. Research directed toward the development of improved switching techniques for inductive power supplies is the subject of this report.

SECTION II INDUCTIVE POWER SUPPLIES AT AEDC-VKF

Two inductive power supplies are currently used at AEDC-VKF to drive arc-heated intermittent hypersonic tunnels. A 10^7 -joule system (Ref. 5) is used to drive a 50-in. hypervelocity tunnel (Gas

*Air Force Systems Command (AFSC)

Dynamic Wind Tunnel, Hypersonic (H)), and a 10^8 -joule system is used to drive a 100-in. hypervelocity tunnel (Gas Dynamic Wind Tunnel, Hypersonic (F)) (Ref. 6) of AEDC-VKF.

2.1 TUNNEL H SYSTEM

The Tunnel H inductive power supply, as used with the wind tunnel, is shown schematically in Fig. 1. This system consists of a unipolar generator, drive motor and coupling, flywheel, energy storage coil, and associated bus and switches. The unipolar generator has a continuous rating of 80,000 amp at 70 v and a pulse rating of 250,000 amp at 70 v for short time pulses. The system was designed to deliver 10^7 joules into a 0.0825-ohm resistive load in 4.12 msec at 20 kv; however, certain components of this system presently limit the maximum available energy to about 5×10^6 joules. A more thorough description of the system was given by Fillers (Ref. 5).

Referring to Fig. 1, the unipolar generator and flywheel system is driven by a 250-hp induction motor which can be engaged or disengaged by means of a magnetic clutch. The generator and flywheel can be brought up to full speed (3550 rpm) in about 20 min. About 50×10^6 joules of kinetic energy are stored in the flywheel at full speed. The induction motor is disengaged from the generator and flywheel assembly at the beginning of the charging cycle, but the generator continues to run by virtue of the momentum of the flywheel. At the same time, a 15-kw dc motor-generator set (0 to 125 v) is connected to the field of the generator, which then develops an electromotive force from 0 to 70 v. With the bus switch S2 remaining open (Fig. 1), the main breaker S1 is closed, sending current through the inductive storage coil. This current rises to about 150,000 amp in approximately 6 sec for a typical case, and the angular velocity of the flywheel is thereby reduced by about 20 percent. The bus switch S2 is closed about 0.2 sec before the current reaches a maximum, thus diverting a small fraction (~ 3 percent) of the current through the magnetic fuse connecting the electrodes (see Ref. 7 for a detailed description of the arc-chamber). This fuse carries the total current for about 10 msec, and during this period the main breaker S1 opens and becomes completely de-ionized. The magnetic fuse then opens from a combination of ohmic heating and induced magnetic forces and initiates the arc. The magnetic fuse thus becomes the final transfer switch for transferring the current to the desired load, i. e., the electric arc within the arc-chamber. It should be noted that the i^2R loss of this switch is not critical since a major portion of this loss appears as i^2R heating of the test gas which is, of course, the desired result. In some runs the duration of the arc is

controlled by the short-circuit switch S3, which can be used to short circuit the arc-chamber (or other load) and thus terminate the discharge process.

2.2 TUNNEL H SYSTEM AS USED WITH AMICOM LASER AND PRESENT FUSE TESTS

A schematic of the Tunnel H inductive power supply as used by Walker and Smithson (Ref. 1) with the AMICOM laser experiments is shown in Fig. 2. The system and its general performance characteristics were identical to that normally used for Tunnel H operation except that the arc-chamber was replaced by a special fuse and the AMICOM load. In contrast with the arc-chamber fuse which initiates and transfers an arc to the electrodes in the arc-chamber, this special fuse was required to extinguish the arc generated by fusing in order to transfer the current into the relatively high impedance AMICOM load. This special fuse must carry the current long enough (≥ 10 msec) for the main breaker S1 to open and de-ionize, during which time the maximum iR drop across the fuse could not exceed 150 v to prevent the restriking of an arc across the terminals of S1. After this initial hold time, the special fuse was required to blow, the resistance of the fusing arc must increase to develop sufficient voltage (≈ 3000 v) to transfer current into the AMICOM load, and then the fusing arc must be extinguished. As mentioned before, Walker and Smithson (Ref. 1) describe the development of a "copper tube" fuse to meet these basic requirements. A typical set of voltage and current traces obtained with the copper tube fuse and the AMICOM laser is shown in Fig. 3. Although nearly 50,000 amp at 3000 v were delivered to the AMICOM load in this case, a comparable amount of energy was consumed in the fuse device.

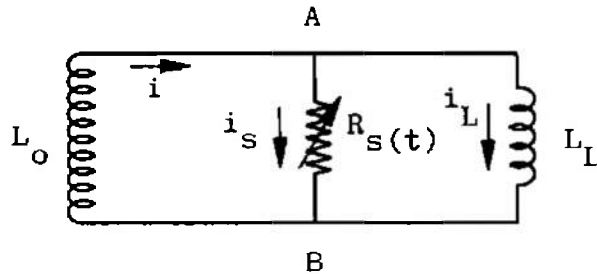
A schematic of the Tunnel H circuit as used for the present research is shown in Fig. 4. Some tests were made with an open circuit (Case I) to simply examine the fuse voltage-current characteristics. Later tests were made with dummy loads (Cases II and III) in place of the actual AMICOM load. Typically, measurements of fuse (or switch) voltage and load voltage (v_s or v_L), fuse current (i_s), load current (i_L), and total current (i) were made as functions of time. Voltage measurements were obtained with voltage dividers, and current measurements were obtained from inductive loops placed around the appropriate buswork.

SECTION III GENERAL SWITCHING CONSIDERATIONS

The existing AEDC-VKF inductive power supplies impose some rather stringent requirements for the final process of transferring

the current to the desired load. The final transfer switch must (1) carry full current at a low voltage level (< 150 v) for a relatively long time period (> 10 msec) to permit the opening and de-ionization of the main breaker S1 and (2) develop the voltage required to transfer into the desired load. In the case of the AMICOM load a master arc-gap was used; thus no current transfer was started until the voltage reached a preset value. It will be show that the second step voltage rise (item 2 above) must occur very rapidly to minimize the energy expended in the transfer process.

Any actual load will, of course, have finite inductance and resistance; thus it is of some interest to examine the minimum energy required to transfer into a purely inductive load. Consider the following circuit



where at $t = 0$, $i_S = i = i_0$, $i_L = 0$ and $R_S = 0$, and at $t = \infty$, $i_S = 0$, $i_L = i$ and $R_S = \infty$. The voltage equations are

$$v_{AB} = v_s = i_s R_s = L_L \frac{di_L}{dt} = -L_o \frac{di}{dt} \quad (1)$$

The switch energy dissipation equation is

$$E_s = \int_0^{\infty} v_s i_s dt \quad (2)$$

The current equation is

$$i = i_s + i_L$$

or

$$\frac{di}{dt} = \frac{di_s}{dt} + \frac{di_L}{dt} \quad (3)$$

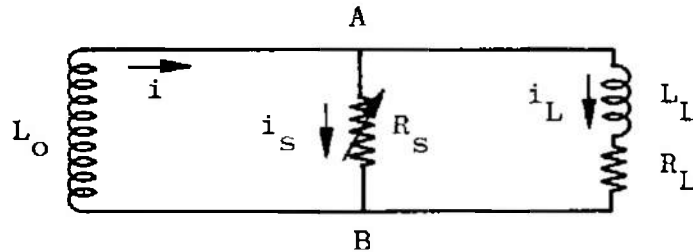
Substituting Eqs. (1) and (3) into Eq. (2) and integrating yields

$$E_s = \frac{L_o L_L i_0^2}{2(L_o + L_L)} \quad (4)$$

therefore,

$$\frac{E_s}{E_o} = \frac{L_L}{L_o + L_L} \quad (5)$$

Note that this result is independent of the transfer time, absolute energy level, or voltage level. Although physical reasoning indicates that this is the minimum energy required to transfer, it can be shown that all additional terms attributable to load resistance are positive; thus this result represents a true minimum. Consider the following circuit with both inductance and resistance in the load



The voltage equations become

$$v_s = i_s R_s = L_L \frac{di_L}{dt} + i_L R_L = -L_o \frac{di}{dt} \quad (6)$$

The energy and current equations (Eqs. (2) and (3), respectively) remain unchanged, thus

$$\frac{E_s}{E_o} = -\frac{1}{E_o} \int_0^\infty \left(L_L \frac{di_L}{dt} + i_L R_L \right) dt \quad (7)$$

or substituting Eqs. (3) and (6) and integrating the first term yields

$$\frac{E_s}{E_o} = \underbrace{\frac{L_L}{L_o + L_L}}_{\text{Loss Attributable to Inductive Load Component}} + \underbrace{\frac{2R_L}{L_o i_o^2} \left(1 - \frac{L_L}{L_o + L_L} \right) \int_0^\infty i_L i_s dt}_{\text{Loss Attributable to Resistive Load Component}} \quad (8)$$

Unfortunately, a general solution to Eq. (8) is not available; however, examination of the resistive term in Eq. (8) reveals that it will always be positive; thus for an arbitrary case

$$\frac{E_s}{E_o} > \frac{L_L}{L_o + L_L} \quad (9)$$

It is also of interest to consider the open-circuit case since the AMICOM load (and possible other future loads) required a master arc-gap preset at the required voltage. Clearly, the energy expended prior to breakdown of the arc-gap must be kept to a minimum to achieve efficient switching. It can be observed in the data of Walker and

Smithson (Ref. 1) that the copper tube fuse produced a near linear voltage rise with time (this will also be shown subsequently in the data presented herein); thus we assume

$$v_s = \bar{k}t$$

where \bar{k} is the average rate of voltage change with time. Let v_a be the preset voltage for breakdown of the arc-gap. The energy expended up to this time is

$$E_{s,a} = \int_0^{t_a} v i dt = \bar{k} \int_0^{t_a} t i dt \quad (10)$$

but

$$v = \bar{k}t = -L_o \frac{di}{dt} \quad (11)$$

therefore,

$$i = i_o - 0.5 \frac{\bar{k} t^2}{L_o} \quad (12)$$

thus

$$\frac{E_{s,a}}{E_o} = \frac{v_o^2}{L_o i_o \bar{k}} \left[1 - \frac{1}{4} \frac{v_a^2}{L_o i_o \bar{k}} \right] \quad (13)$$

Note that for $\frac{E_{s,a}}{E_o} \ll 1$

$$\frac{E_{s,a}}{E_o} \approx \frac{v_a^2}{L_o i_o \bar{k}} \quad (13a)$$

Therefore, a given expenditure of energy from a given power supply condition will require the voltage rise time (\bar{k}) to increase as the square of the required initial voltage to the load circuit. The energy loss discussed previously (Eqs. (9)) will be in addition to the above loss since the above loss comes about in simply producing the conditions required to start the actual transfer process.

Equation (13a) has been plotted in Fig. 5 to indicate the order of required voltage rise times. The regime of the data from Walker and Smithson (Ref. 1) is also noted. It is clear that at least an order increase in the voltage rise times obtained by Walker and Smithson will be required to produce an efficient transfer switch for use with a preset arc-gap.

In summary of the theoretical considerations, it has been shown that an efficient transfer switch will require nearly a step voltage rise, and even then, a minimum energy must be expended in the switch itself. The voltage level must, of course, be equal to or greater than the iR drop across the intended load.

SECTION IV SWITCH DEVELOPMENT

4.1 COPPER TUBE FUSE

The copper tube fuse used previously by Walker and Smithson (Ref. 1) was re-examined to determine if (1) the operating voltage could be increased, (2) the current level could be increased, and primarily (3) the efficiency could be improved. The principles of the copper tube fuse were discussed by Walker and Smithson. A sketch and photograph of the copper tube fuse are shown in Fig. 6a. Tests at less than 100,000 amp were conducted with a single tube, as shown in Fig. 6a. Two identical tubes were clamped together for tests at 100,000 amp or greater.

Tests were made with the open-circuit arrangement shown in Fig. 4 (Case I), and the test current was raised from 60,000 to 108,000 amp. The tests were conducted, for safety reasons, inside an 8-ft-diam steel blast tank. The voltage-current-time characteristics from these tests are shown in Fig. 7. The zero reference time was taken as the initiation of fuse break as estimated from the oscilloscope traces. The peak voltage obtained was approximately $0.08 i_o$, except for the flat portions of the voltage traces which occurred during the later part of the discharge process. This is believed to be caused by interference between the magnetically blown arc and the blast tank walls. This apparent interference with the blast tank walls also limited the current range of the present tests since higher currents would have produced earlier interference.

The relative energy losses of the copper tube fuse up to specific voltage levels have been computed from the measured voltage-current characteristics and are shown in Fig. 8. It is interesting to note the decreasing relative loss, at a given voltage level, with increasing initial energy level. It should, however, be noted that a given load (i.e., fixed resistance) will require an increasing voltage with increasing energy; thus the relative energy loss may, in fact, increase, depending on the specific load and energy levels.

Examination of the voltage-time curves of Fig. 7 shows that the maximum obtained average rate of voltage rise (\bar{k}) was approximately 1.5×10^6 v/sec. This is in close agreement with the lower voltage data from Ref. 1, and referring to Fig. 5, it can be seen that this is far short of the rate required for an efficient fuse.

4.2 SAND FUSE

A "sand" fuse was constructed by soldering 25 No. 16 bare copper wires to copper end plates and imbedding the copper wires in dry mortar sand. A sketch and photograph of the sand fuse are shown in Fig. 9. The mortar sand was contained, as shown, by an insulating material. The basic idea here was to quench the arc resulting from vaporization of the copper wires with the dry mortar sand. The experimental voltage-time characteristics of the sand fuse are shown in Fig. 10 for two lengths of wires, 24 and 12 in. The maximum average rate of voltage rise was found to be nearly 4×10^6 v/sec. This value, although over twice the copper tube face value, is still far short of the increase desired.

4.3 GUN SWITCH

The concept of the so-called "gun" switch evolved from considerations of how to produce a very rapid, ($\sim 10^8$ -v/sec) voltage rise. The basic idea is to propel at high speed an insulator into a conducting column and literally squeeze the column between two insulators. The original design of the gun switch used a low voltage arc as the conductor. A sketch of the initial gun switch is shown in Fig. 11. The electrical end of the gun switch (Fig. 12) is, in effect, a coaxial arc-chamber using a magnetic fuse as developed for the hotshot arc-chambers (Ref. 4) to initiate the low voltage arc. After generation of the low voltage arc, a polyethylene piston was driven into the arc. Smokeless powder was used as the propellant, and typically, a piston velocity of about 2000 ft/sec was used. Before firing, the gun tube was evacuated to a pressure of about 0.5 torr. Exhaust ports, initially sealed with blowout plugs, were located in the fuse base. These plugs were designed to blow out at a pressure level just slightly above atmospheric. The purpose of the blowout plugs was to prevent excessive slowdown of the piston caused by high gas pressure before its impact with the conducting gas column and the rear insulator. As noted in Fig. 11, the positive bus from the power supply was connected to the center electrode, and the gun tube itself was connected to the negative bus.

The firing sequence was as follows: (1) switch S2 was closed to divert current through the gun switch, (2) the magnetic fuse holds long enough for the main breaker to open and de-ionize, (3) the magnetic fuse breaks, creating a low voltage arc (< 300 v), (4) the arc voltage rise is used as a signal to ignite the primer which, in turn, ignites the smokeless powder, and (5) the piston impacts and produces a sharp voltage rise. A typical data trace showing the above sequence of

events is shown in Fig. 13. This trace was obtained with the open-circuit arrangement (Fig. 4, Case I) discussed previously.

Although the initial design of the gun switch produced very sharp voltage rises, a number of problems was encountered. The low voltage arc burned for approximately 7 msec before piston impact. This generated gas pressure which, in turn, reduced the piston velocity. Although this velocity loss could, in principle, be compensated for by the use of increased quantities of gunpowder, the stress level on the gun was apparently quite high; thus only modest changes could be made. The arc-heated hot gas exhausting through the rear blowout ports was also quite troublesome. This hot gas frequently caused external arcing in the buswork connections.

Several failures occurred because of mechanical rupture of the insulation around the center electrode and resulting internal arcing. Insulation materials such as nylon, fluorocarbon polymers, and glass fiber epoxy were tested and would not stand the high impact loads. High density polyethylene was the most satisfactory insulating material tested, and even in this case it was found necessary to increase the thickness of the insulation in critical areas to compensate for the plastic flow of the polyethylene.

Experience gained from the initial design and a number of component changes led to the evolution of the final gun switch design shown in Fig. 14. In this case, the magnetic fuse was replaced with a copper ribbon conductor which carried the current during the operation of switches S1 and S2 and remained in place until sheared by the piston and folded into a recessed area. Single or double conductors, Figs. 14a and b, respectively, could be used with this arrangement. This scheme eliminated the objectionable low voltage arc of the initial design. The exhaust ports were relocated on the sides of the gun tube to eliminate the discharge of hot gases in the vicinity of the center electrode and the connecting buswork. The firing sequence was revised to initiate combustion of the gunpowder ≥ 10 msec after the time the current rise was detected in the gun switch ribbon conductors.

The open-circuit arrangement (Fig. 4, Case I) was used during a few initial shots in an attempt to optimize the piston weight and gunpowder loading and to study the open-circuit voltage rise times. The polyethylene piston weight was varied from 229 to 513 gm, and the propellant loading was varied from 100 to 150 gm of smokeless powder. The 150 gm of powder produced failure of the polyethylene insulation and the base of the center electrode; thus the powder charge was limited to 125 gm. Direct measurements of piston velocity were

not made; however, from the combustion chamber pressure traces, the tube pressure traces and the voltage traces, an approximate estimate of piston velocity can be made. The terminal velocity was estimated to be about 2000 ft/sec for the case with 125 gm of powder and a 330-gm piston. These tests were made at a current level of 25,000 amp, and typical results are shown in Fig. 15. Voltage rise rates of 4×10^8 v/sec were obtained. Referring to Fig. 5, it is indicated that voltage rise rates of this order offer the possibility of very efficient energy transfers.

To study the transfer characteristics of the gun switch into an actual load, a 0.06-ohm, 6- μ h load (Fig. 4, Case II) was paralleled with the gun switch. The resistance of a single-ribbon conductor was approximately 0.0006 ohms; thus only a small fraction of the current would be initially shunted through the actual load. This load was paralleled directly across the gun switch without an arc-gap, as had been previously used with the copper tube fuse and the AMICOM load. The very high voltage rise rates available with the gun switch eliminate the necessity for the arc-gap. A typical oscillograph data trace is shown in Fig. 16. On this time scale the transfer appears to take place as a step function; however, oscilloscope traces on a faster time scale reveal that the transfer process typically took 100 to 150 μ sec with a single-ribbon conductor at a current level of 25,000 amp using a 330-gm piston and from 100 to 125 gm of smokeless powder. Attempts to significantly increase the current level with the single-ribbon conductor were unsuccessful.* The double-ribbon conductor was tested with the same load (Fig. 4, Case II), and it was found that currents up to 35,000 amp could be transferred with this arrangement. The double-ribbon conductor was also tested with an increased impedance load (Fig. 4, Case III), ($R_L = 0.12$ ohms, $L_L = 10 \mu$ h), and a current of 25,000 amp was successfully transferred into this load. Typical oscilloscope current and voltage traces for some of the successful runs are shown in Fig. 17a. Data obtained during a couple of malfunctions are shown in Fig. 17b. In the first case on Fig. 17b, a successful transfer was never obtained. However, in the second case an initially successful transfer was obtained, but after about 560 μ sec an insulation failure occurred, and the gun switch again took over most of the current.

The various shot conditions made on the gun switch are listed in Table I, and the successful transfers are also tabulated in Table II.

*Although one successful transfer was made at 31,500 amp, consistent transfers could not be made above 25,000 amp.

Approximate graphical integration of the voltage-current-time characteristics of the gun switch was accomplished to determine the energy consumption of the switch as tabulated in Table II. The gun switch relative energy losses (E_s/E_o) are summarized in Fig. 18 for all runs for which valid data were obtained. It is interesting to note that the gun switch is a go- or no-go-type switch, i. e., it is very efficient whenever a proper transfer occurs, but quite poor performance is exhibited for partial transfers. It is also interesting to note from Fig. 18 that the successful transfers with the gun switch occur with essentially the theoretical minimum expenditure of energy; thus no further improvement in efficiency of this switch can be expected for these conditions. In the same context, it is observed that all of the successful transfers with the single-ribbon conductor occurred with an electrical energy loss in the gun switch of between 1800 and 3000 joules. Successful transfers with the double-ribbon conductors occurred with losses of about 3000 to 6000 joules or near twice the single-conductor losses. The phenomenon which limits the present energy level for successful application of the gun switch is not understood; however, the above cited results indicate that a critical energy loss density may exist. This was the hypothesis made before the double-ribbon conductor was tested, and certainly a higher energy level can be successfully transferred with this arrangement.

The question of scaling-up, i. e., increasing the energy transfer ability, of the present gun switch is of considerable practical importance since the existing AEDC-VKF inductive power supplies have energy level capabilities from 50 to 500 times the capability of the present gun switch. Unfortunately, the present experiments cover such a narrow range of energy levels and physical parameters that a firm basis for extrapolation of the present design does not exist. Based on the previously discussed possibility of a limiting energy density for a given gun, it is expected that the gun switch critical energy will increase at least with the square of the gun tube diameter (i. e., a constant critical energy per unit area). Since the voltage should increase as some function of the effective arc length which will, in turn, be some function of the tube diameter, an even greater power of the diameter may be involved; however, further experiments will be necessary to determine the scaling rules.

SECTION V CONCLUDING REMARKS

The voltage rise rates for the copper tube fuses, sand fuses, and the gun switch are summarized and compared to the previously discussed desired voltage rise rates from Fig. 5 in Fig. 19. The gun

switch offers voltage rise times two orders of magnitude greater than the other types of fuses; however, the allowable current level is far below the desired level. The electrical transfer efficiency of the gun switch has been shown to be very high, in fact, essentially at the theoretical maximum for the successful transfers. The gun switch represents in reality a device permitting a trade-off between cheap gunpowder energy and relatively expensive electrical energy. Since the combustion of 100 gm of smokeless gunpowder releases approximately 42,000 joules, the absolute overall efficiency of the gun switch is only 70 to 80 percent, as compared to an electrical efficiency from 97 to 98 percent. The gunpowder cost is, however, negligible as compared to cost of the electrical energy from an inductive storage system.

It is clear that the present gun switch was operated near its structural limits, and several of the unsuccessful transfers were caused by the structural failure of critical components. The design of an operational gun switch should include adequate design margins to allow for the difficulty of estimating impact loads. Generalized optimum values of piston mass, piston velocity, gun tube length, initial charge gas composition, and density were not determined during the present research; rather, a specific piston material, piston mass, gunpowder charge was determined empirically for the present gun switch. Further experiments will be required to optimize the many parameters involved and to determine the basic scaling rules for building higher energy versions of the gun switch.

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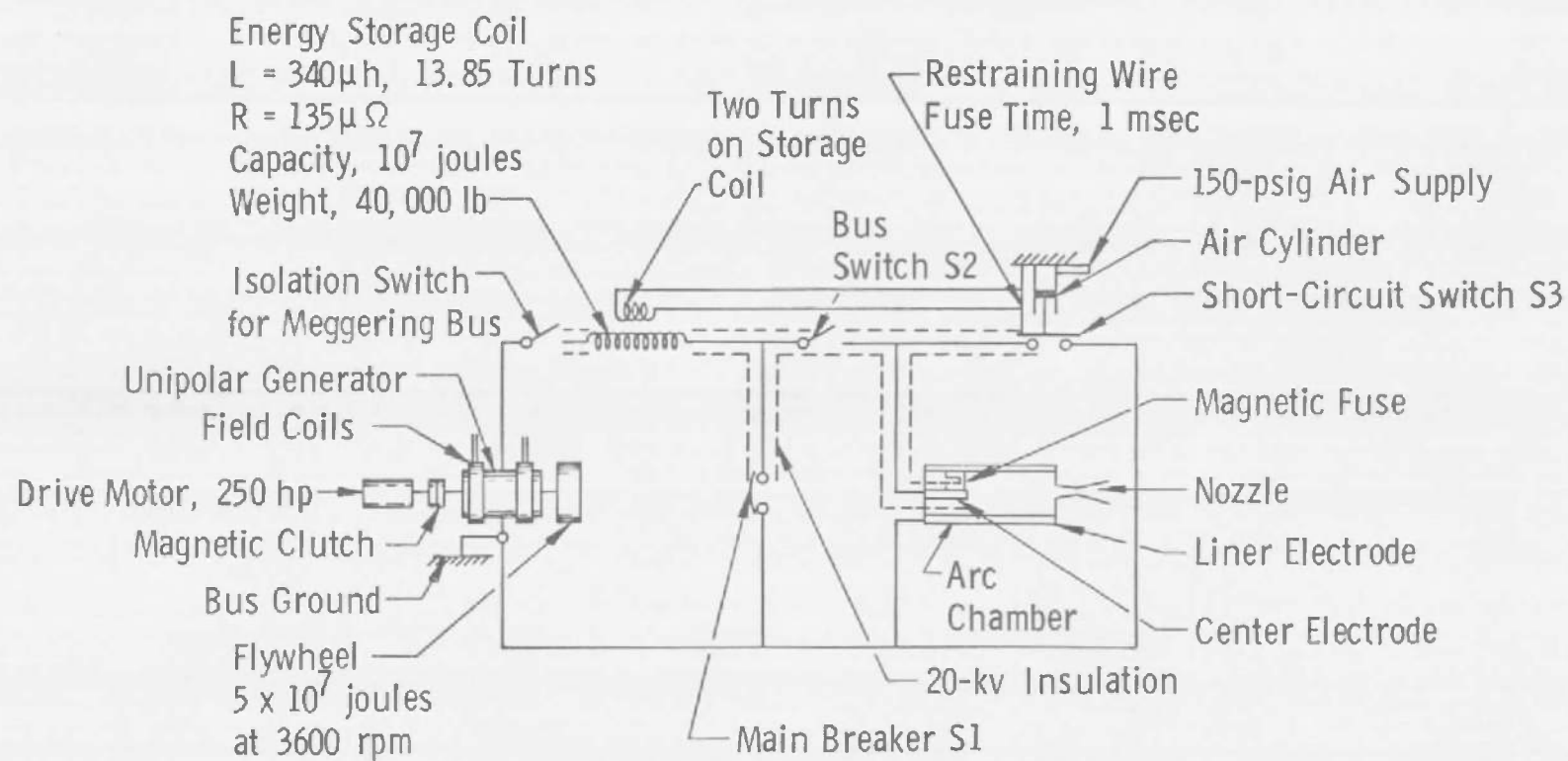


Fig. 1 Schematic of Tunnel H Inductive Power Supply

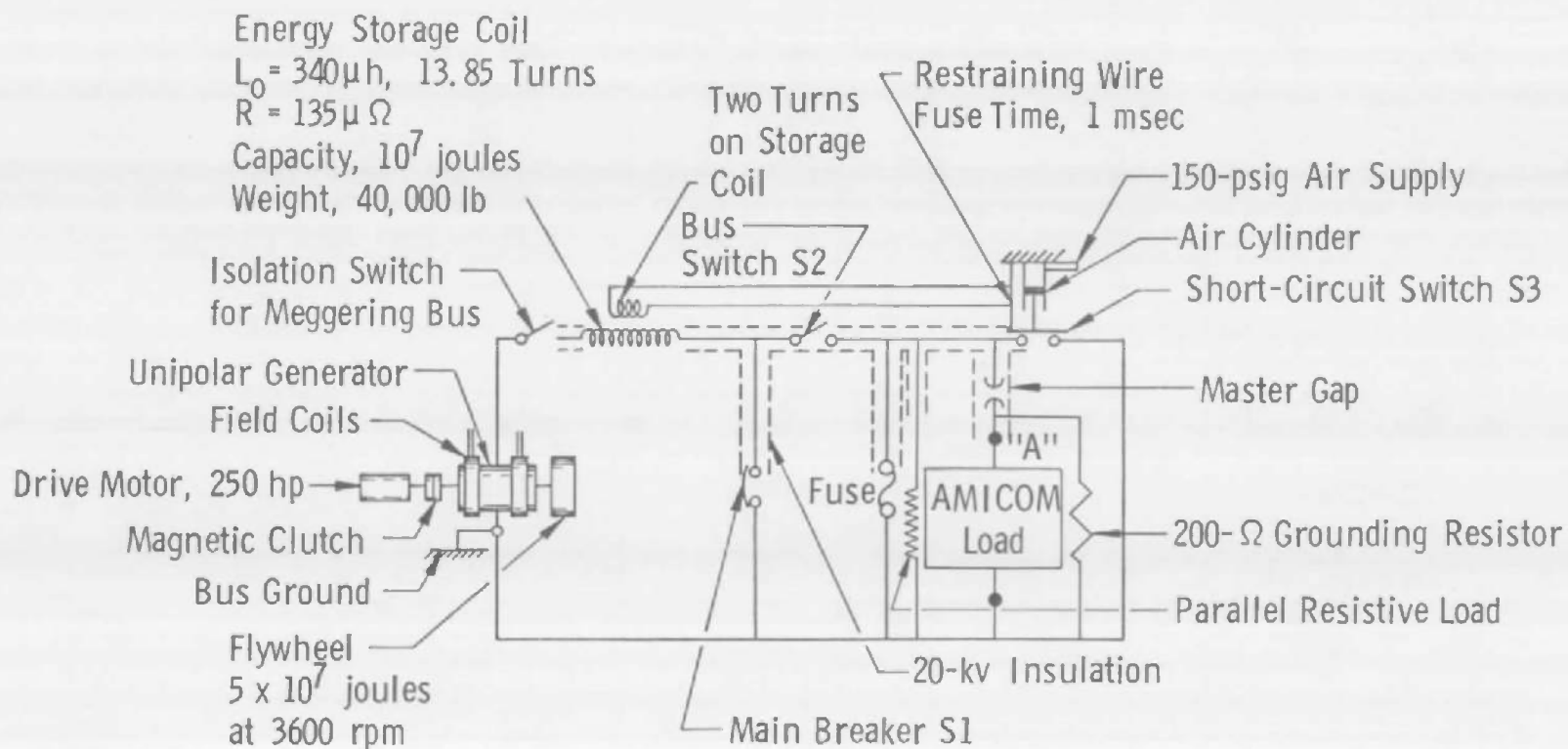


Fig. 2 Schematic of Tunnel H Inductive Power Supply as Used with AMICOM Laser Experiments

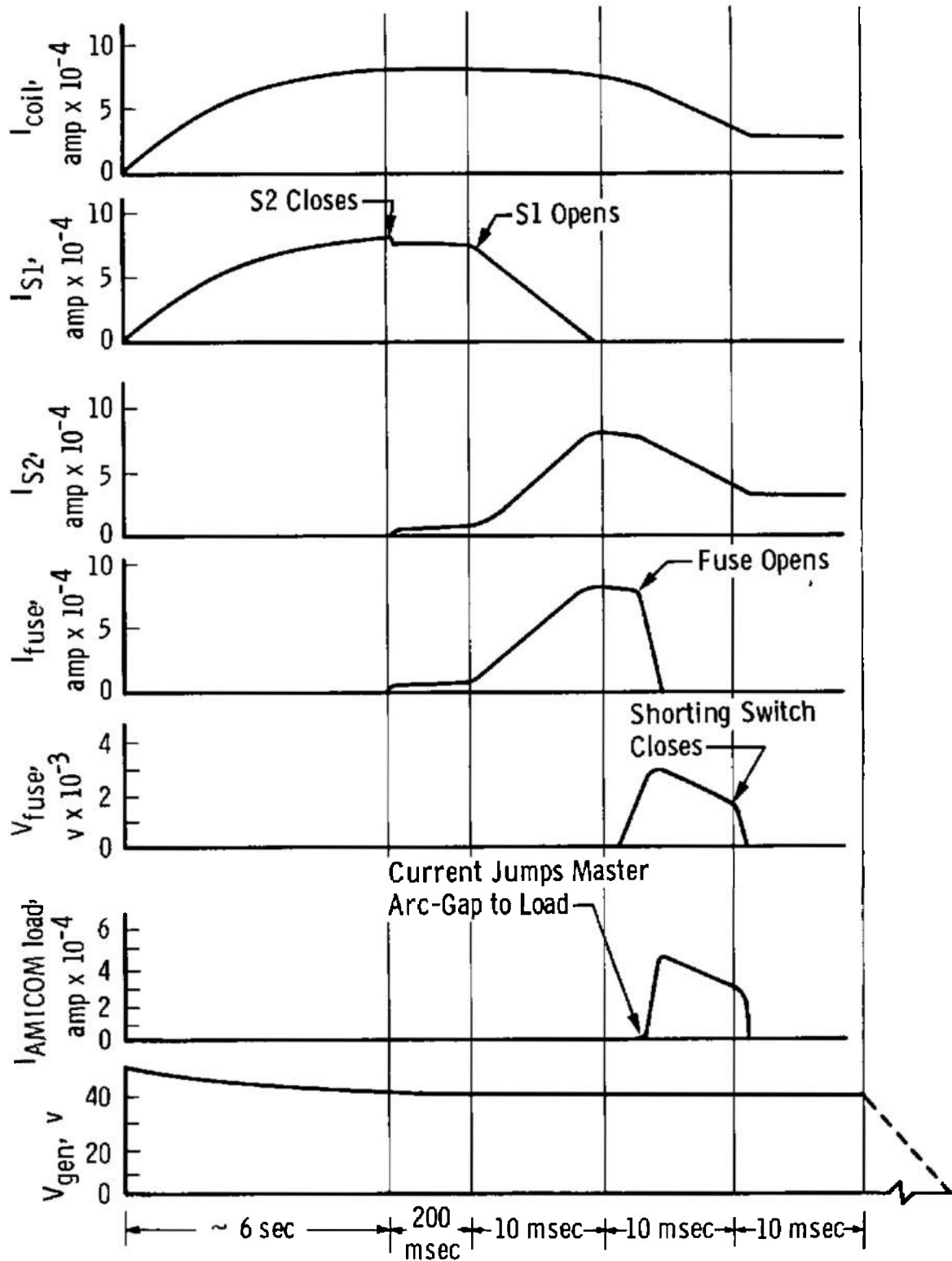
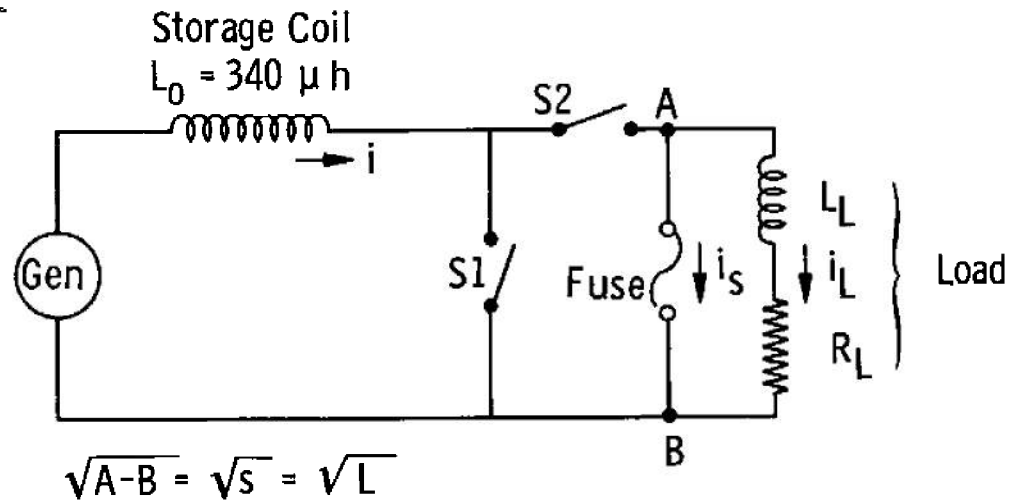


Fig. 3 Typical Traces of Tunnel H Inductive Power Supply as Used with the AMICOM Laser



Present Tests:

Case I - Open Circuit, $R_L \rightarrow \infty$

Case II - $L_L = 6 \mu h$, $R_L = 0.06$ ohms

Case III - $L_L = 10 \mu h$, $R_L = 0.12$ ohms

Fig. 4 Schematic of Tunnel H Circuit for Present Fuse and Gun Switch Tests

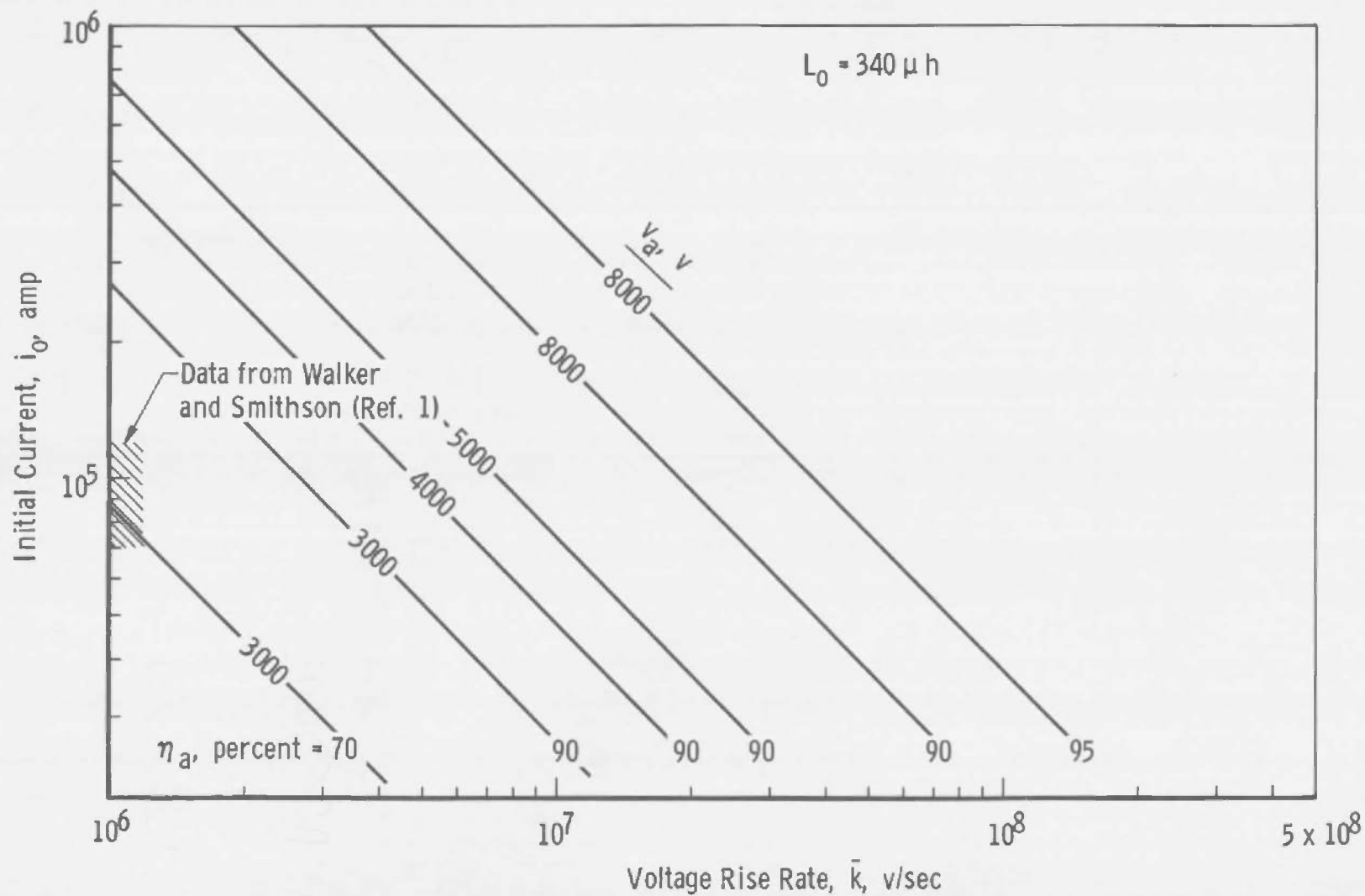


Fig. 5 Voltage Rise Rates Required for Use with a Master Arc-Gap

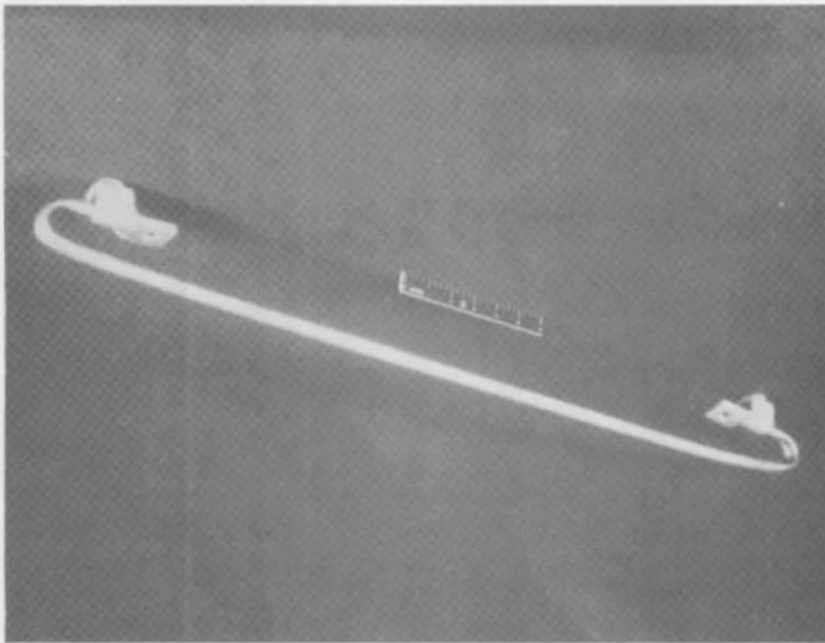
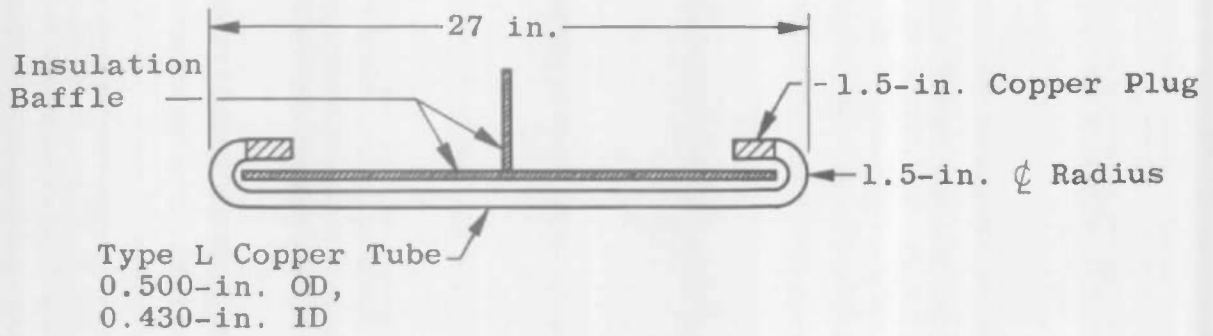


Fig. 6 Copper Tube Fuse

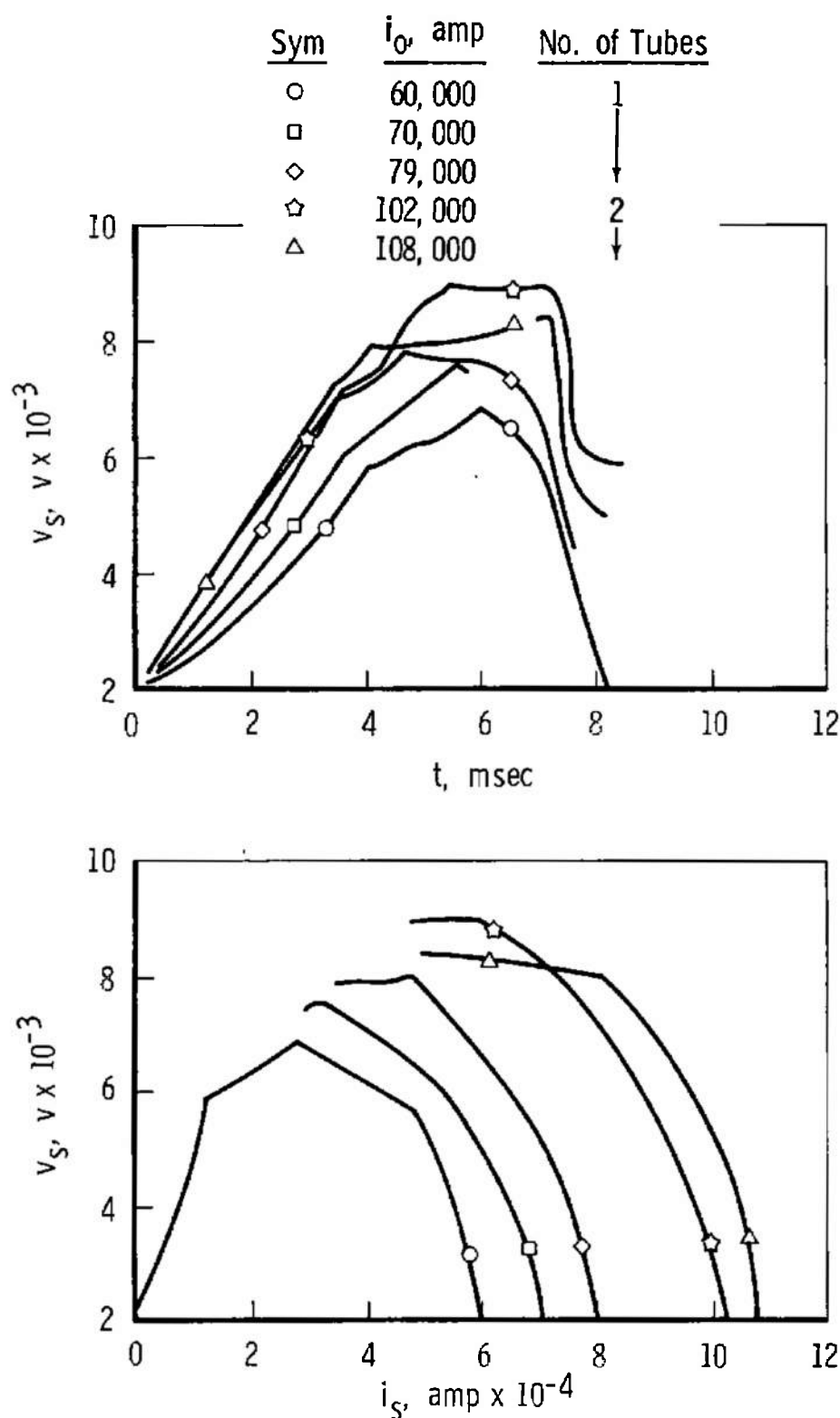


Fig. 7 Voltage-Current-Time Characteristics of Copper Tube Fuse with No Load (Open Circuit)

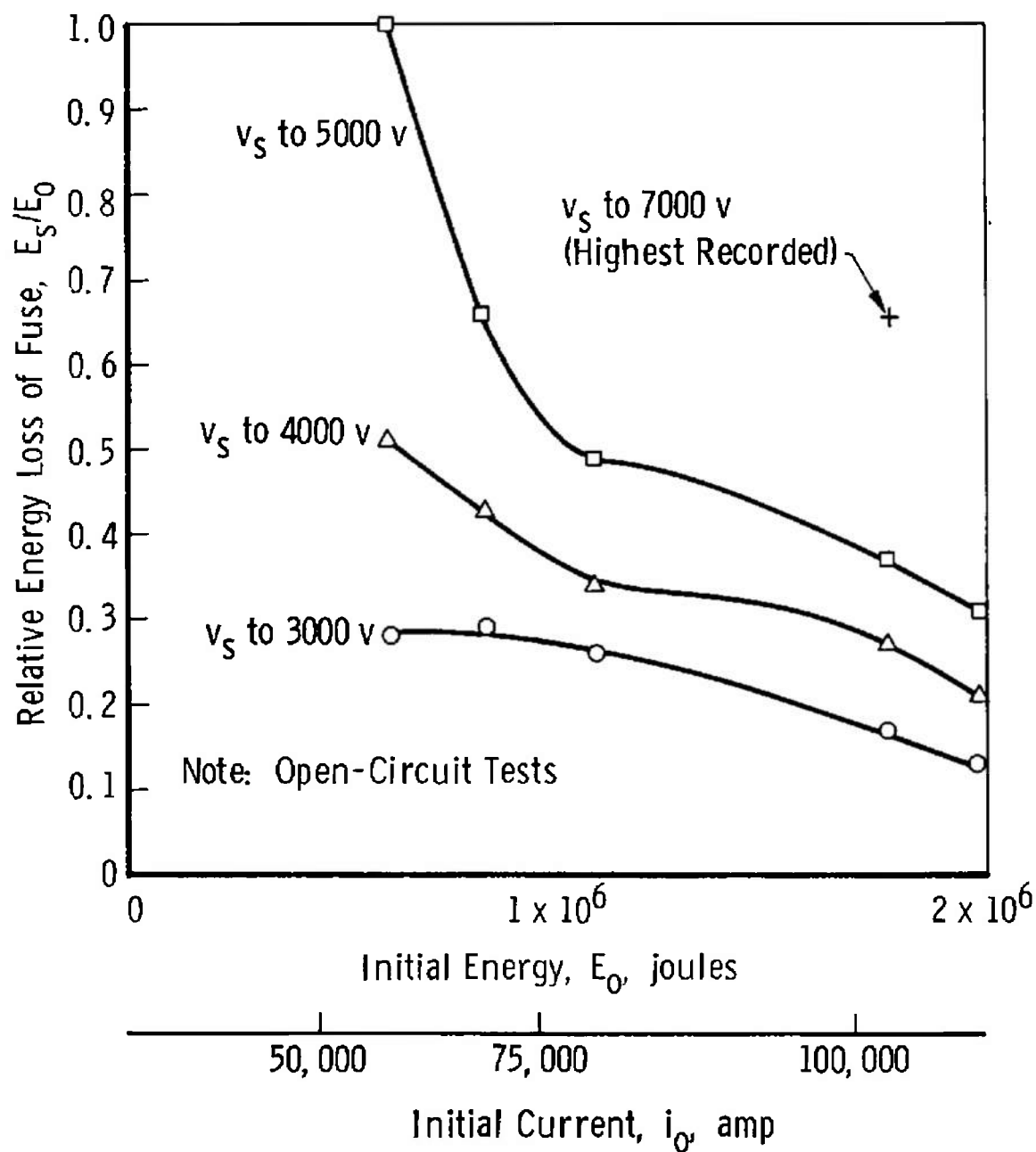


Fig. 8 Relative Energy Losses of the Copper Tube Fuse up to Specific Voltage Levels

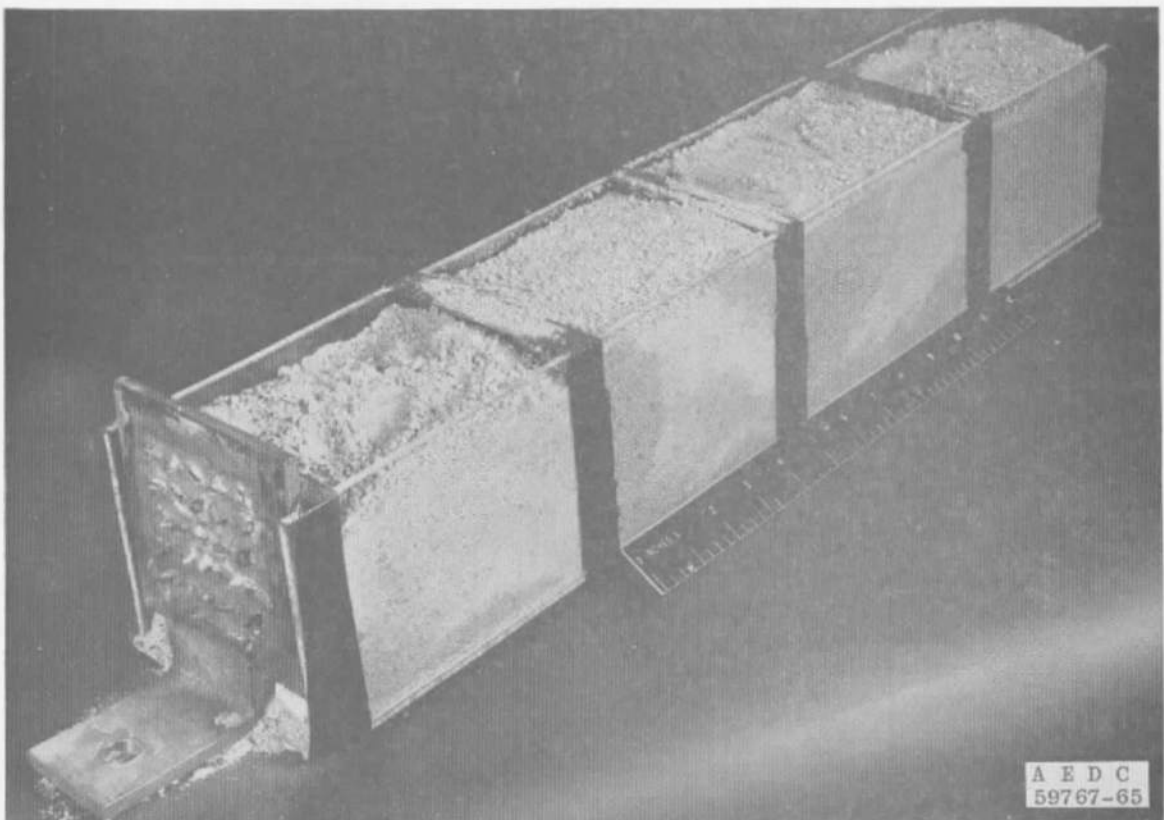
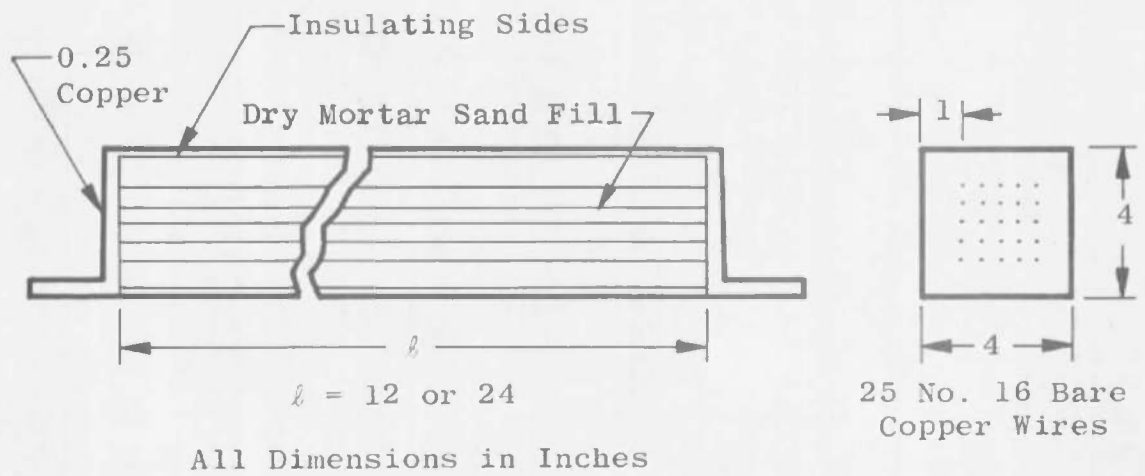
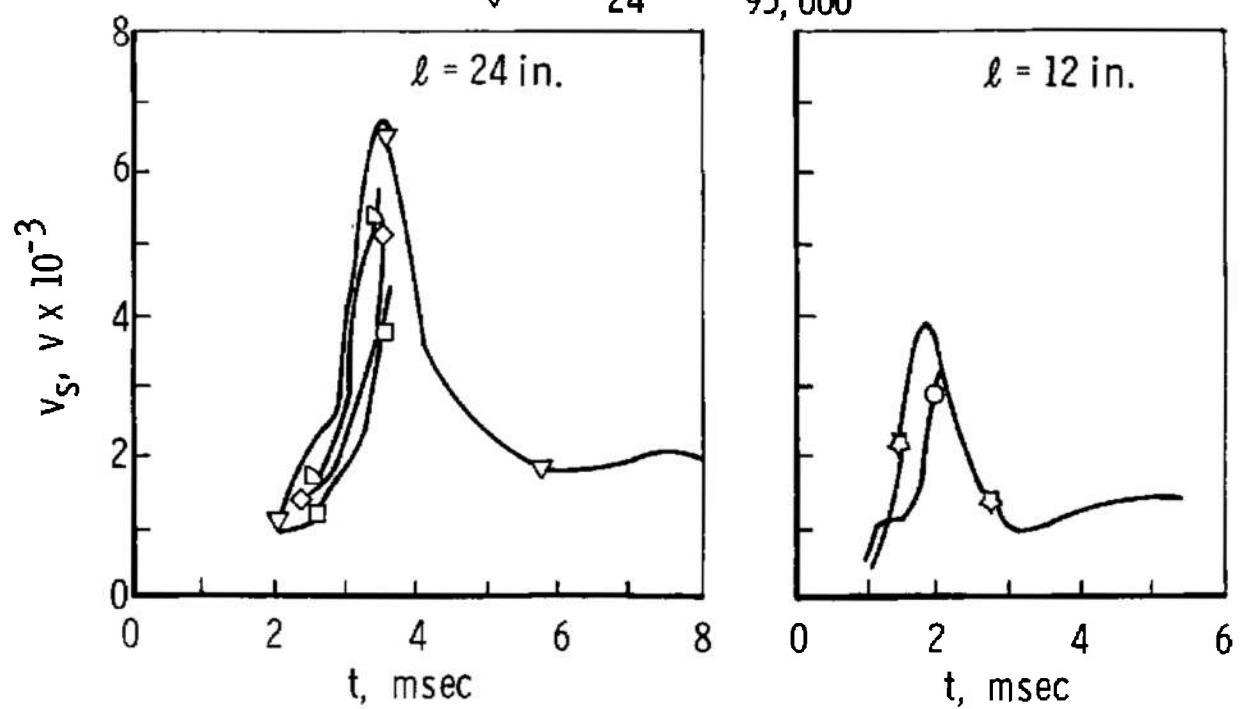


Fig. 9 Sand Fuse

Sym	ℓ , in.	i_0 , amp
○	12	81,500
☆	12	81,000
□	24	81,500
◇	24	83,600
▷	24	94,000
▽	24	93,000



Note: Zero time is arbitrary.

Fig. 10 Voltage-Time Characteristics of Sand Fuse

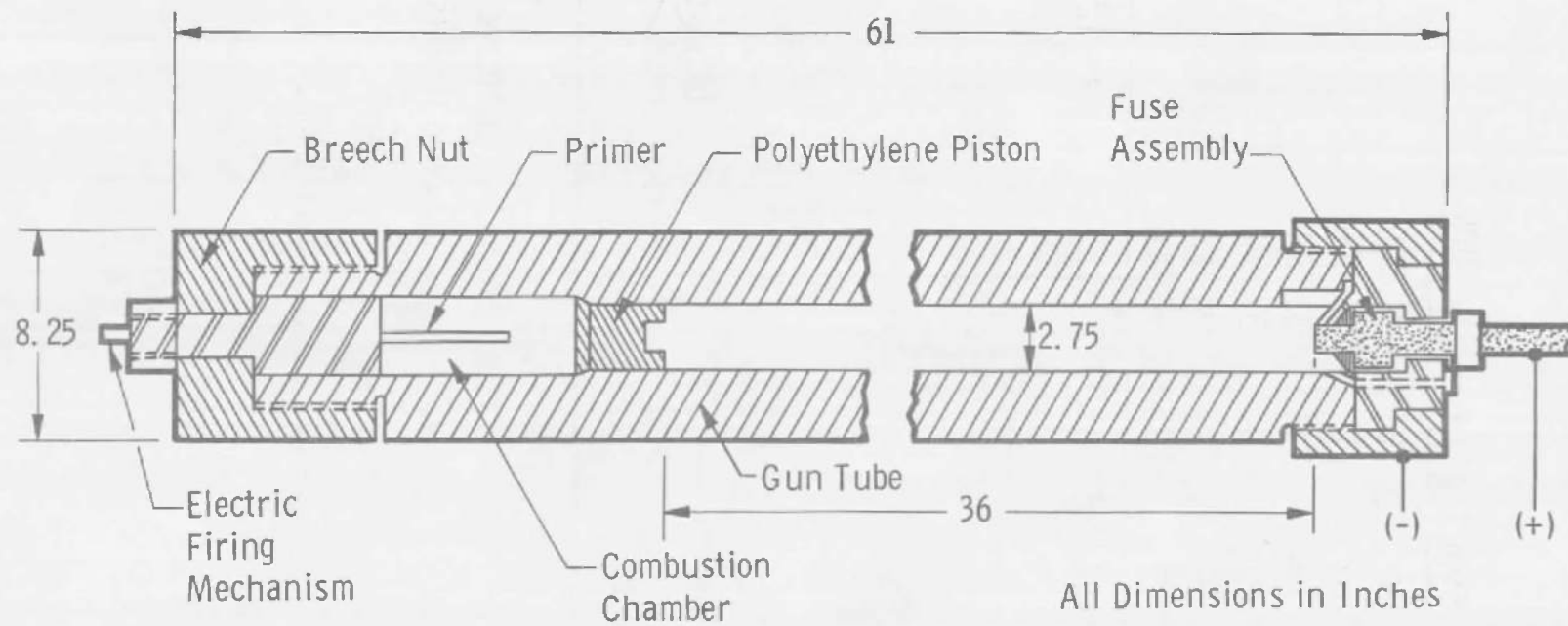
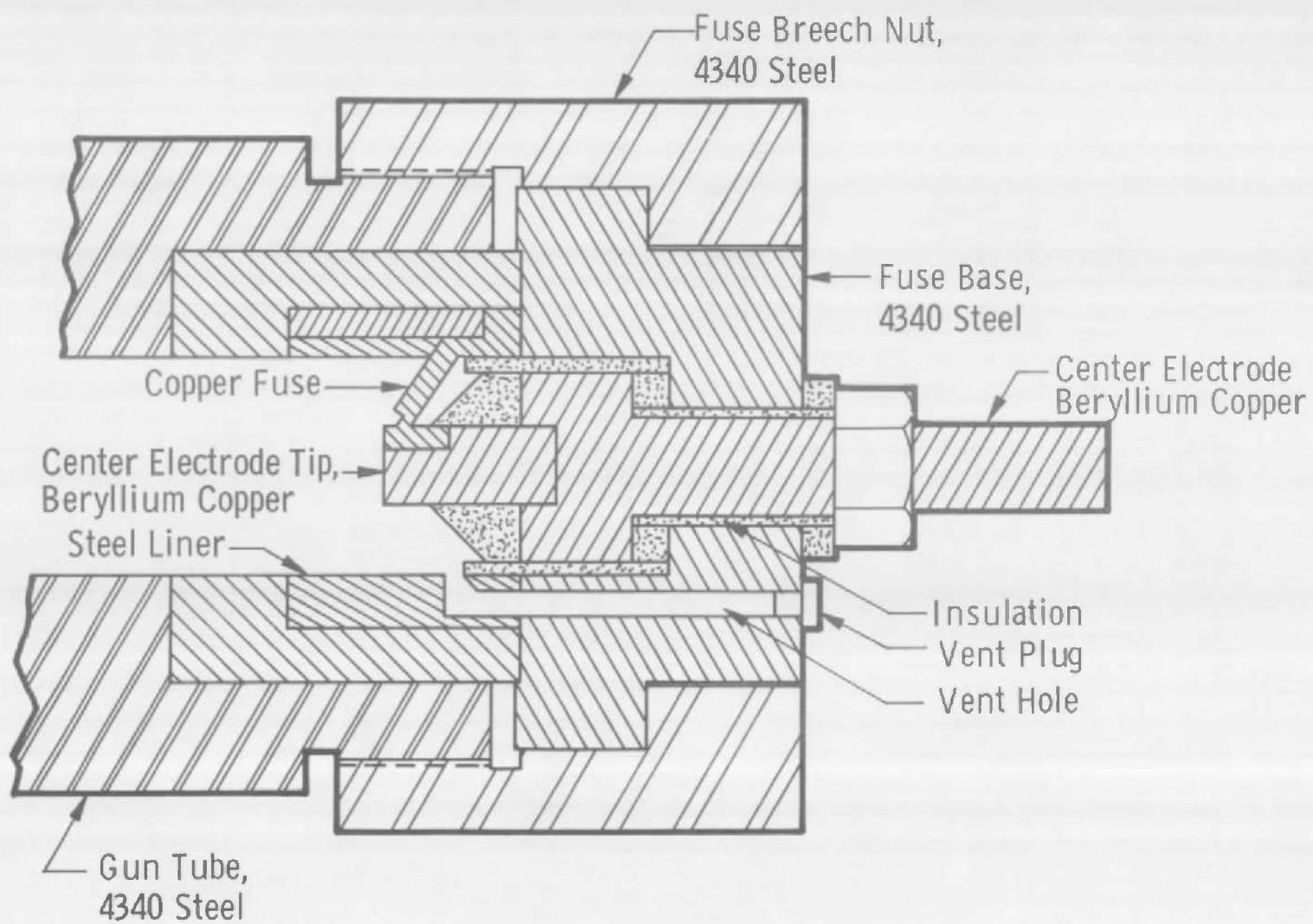
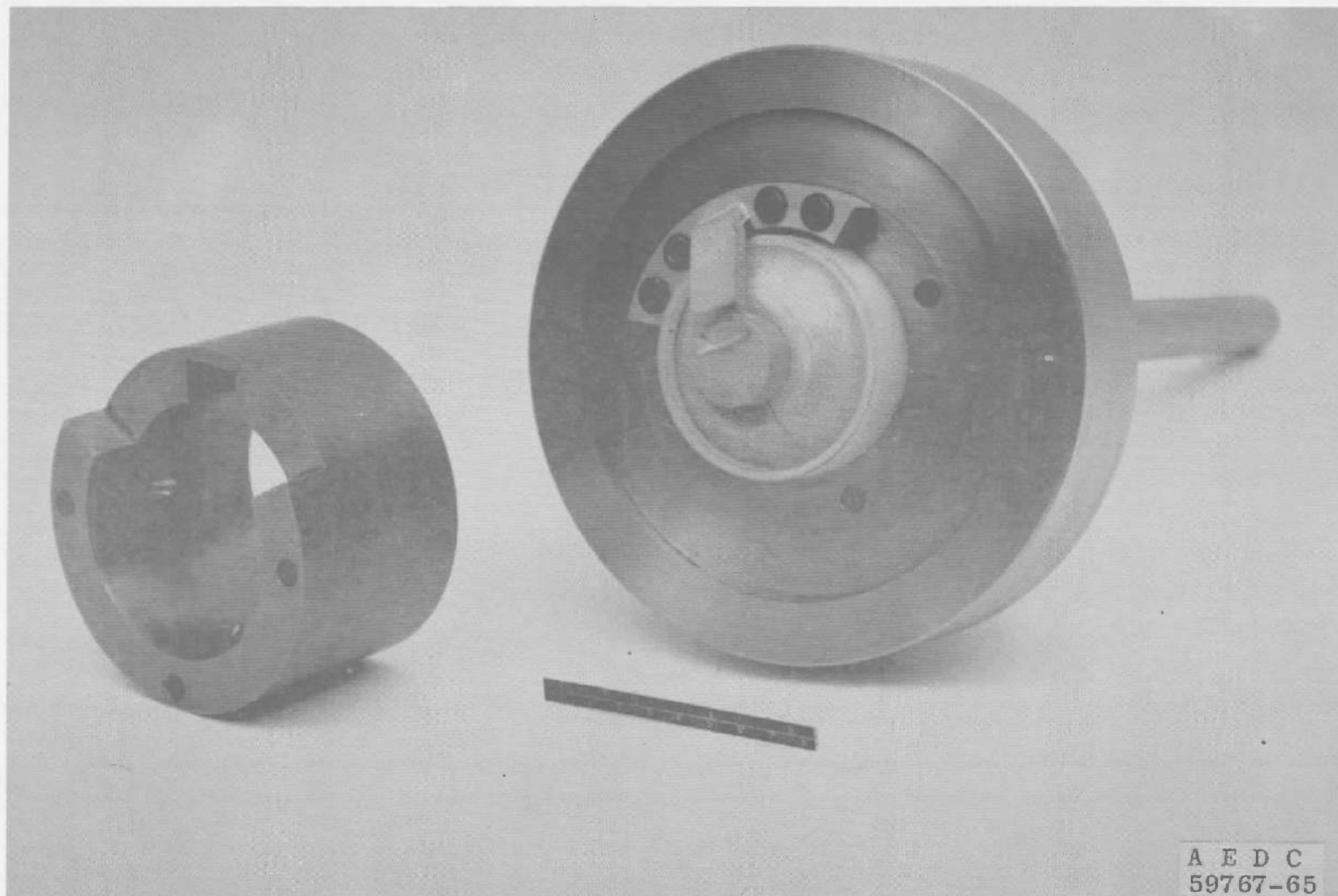


Fig. 11 Sketch of Gun Switch



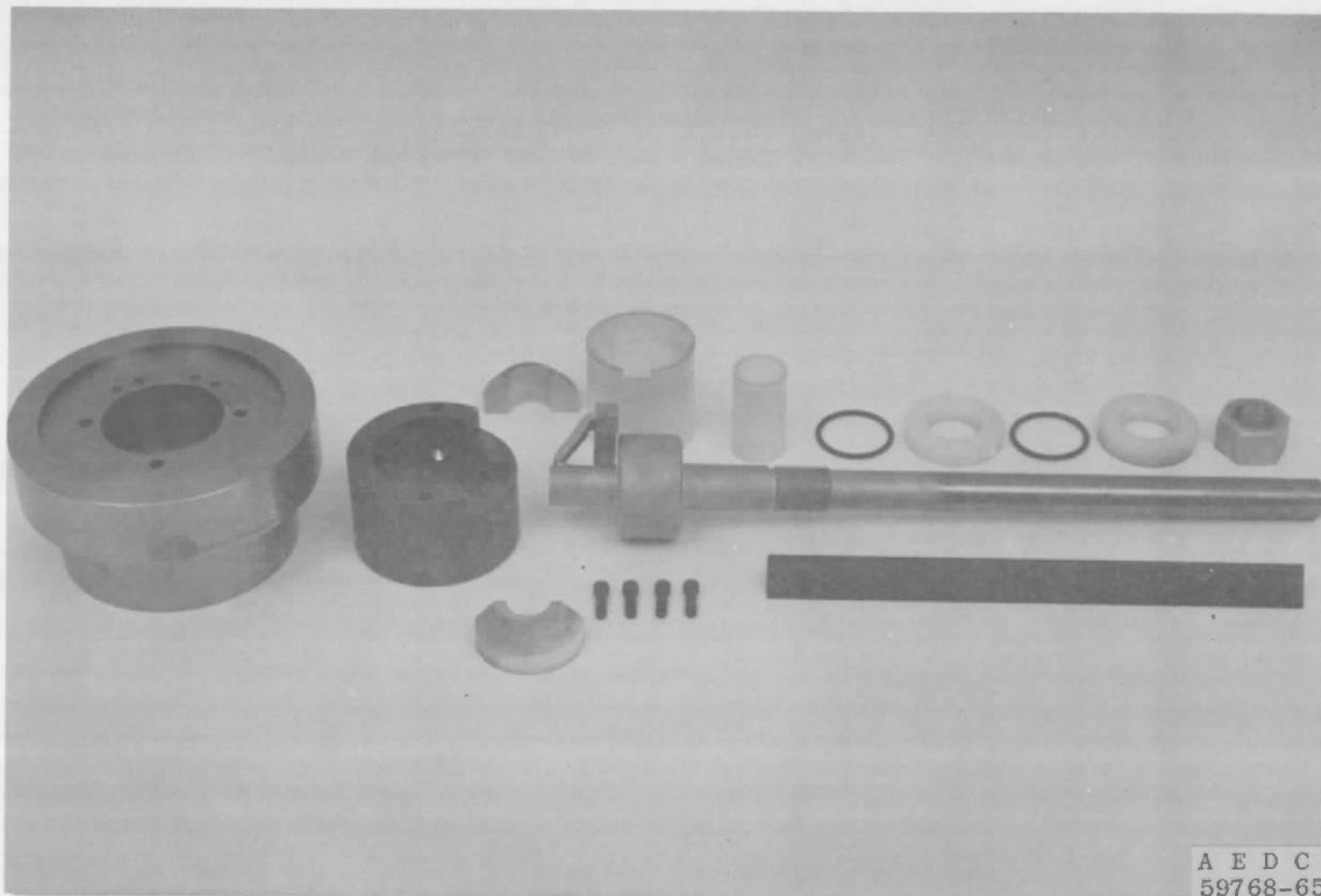
a. Sketch

Fig. 12 Details of the Gun Switch Magnetic Fuse



b. Assembled View of Gun Switch Magnetic Fuse

Fig. 12 Continued



c. Exploded View of Gun Switch Magnetic Fuse

Fig. 12 Concluded

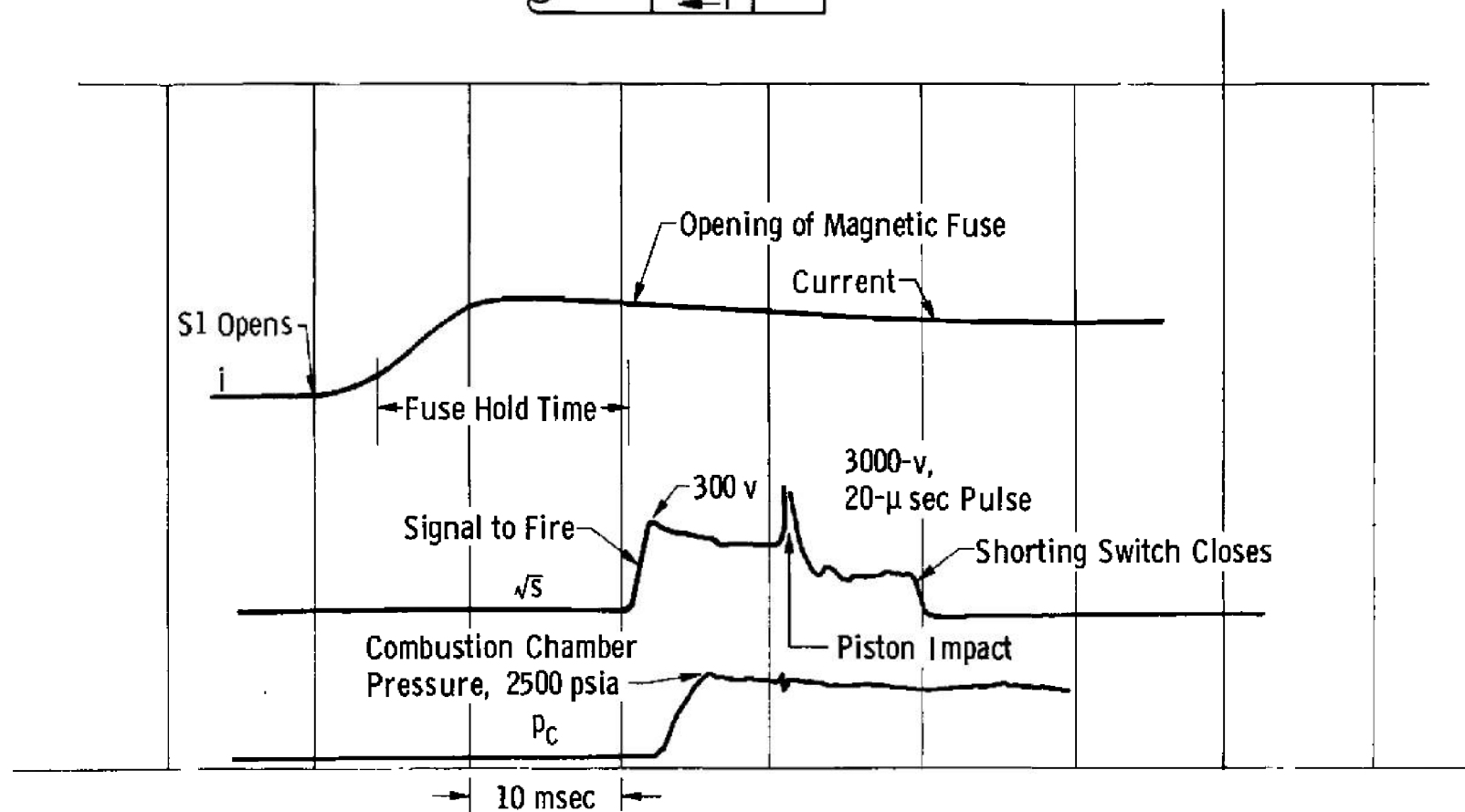
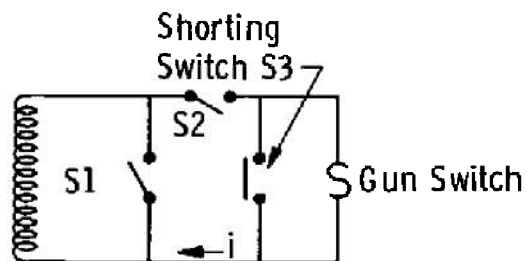
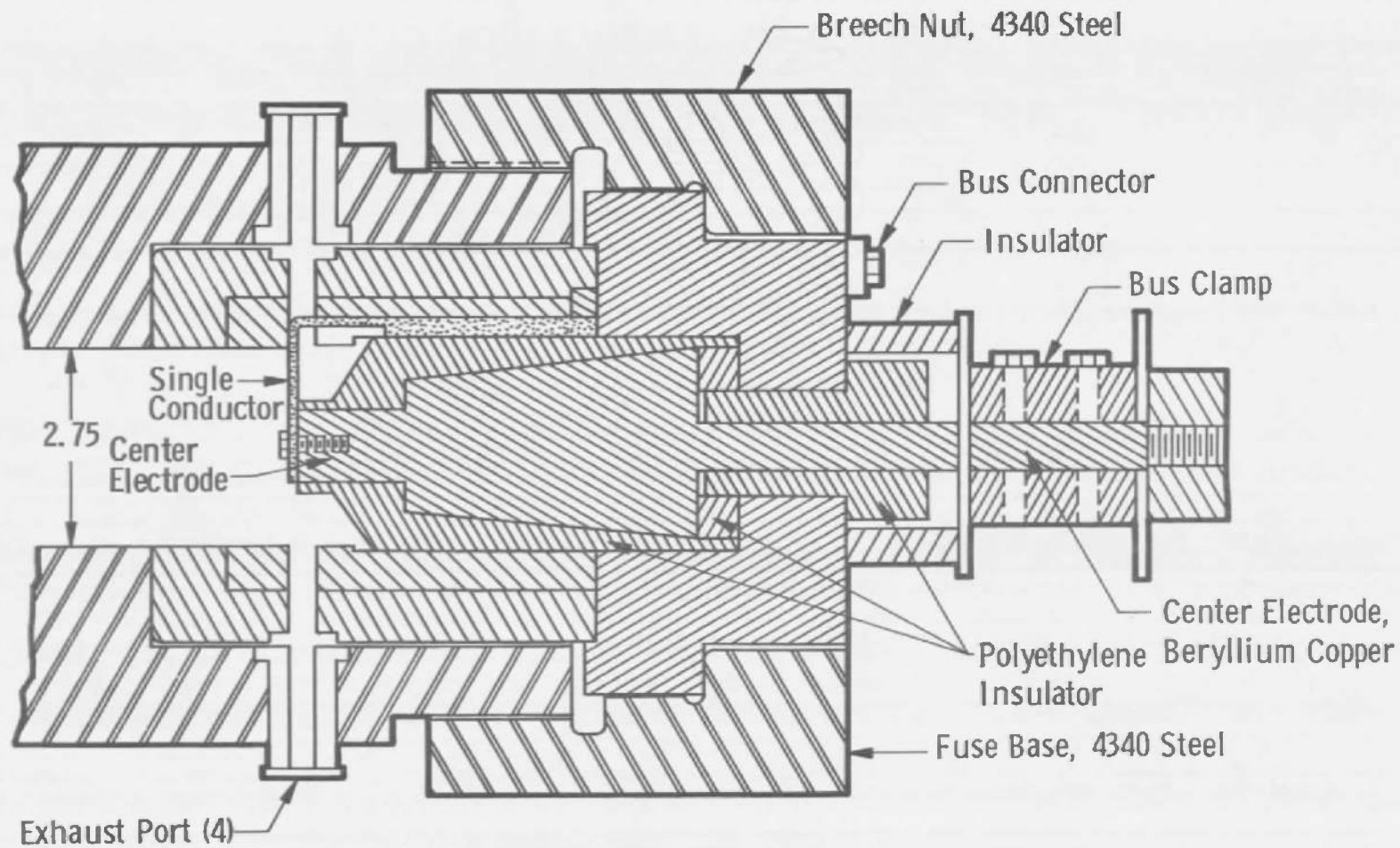
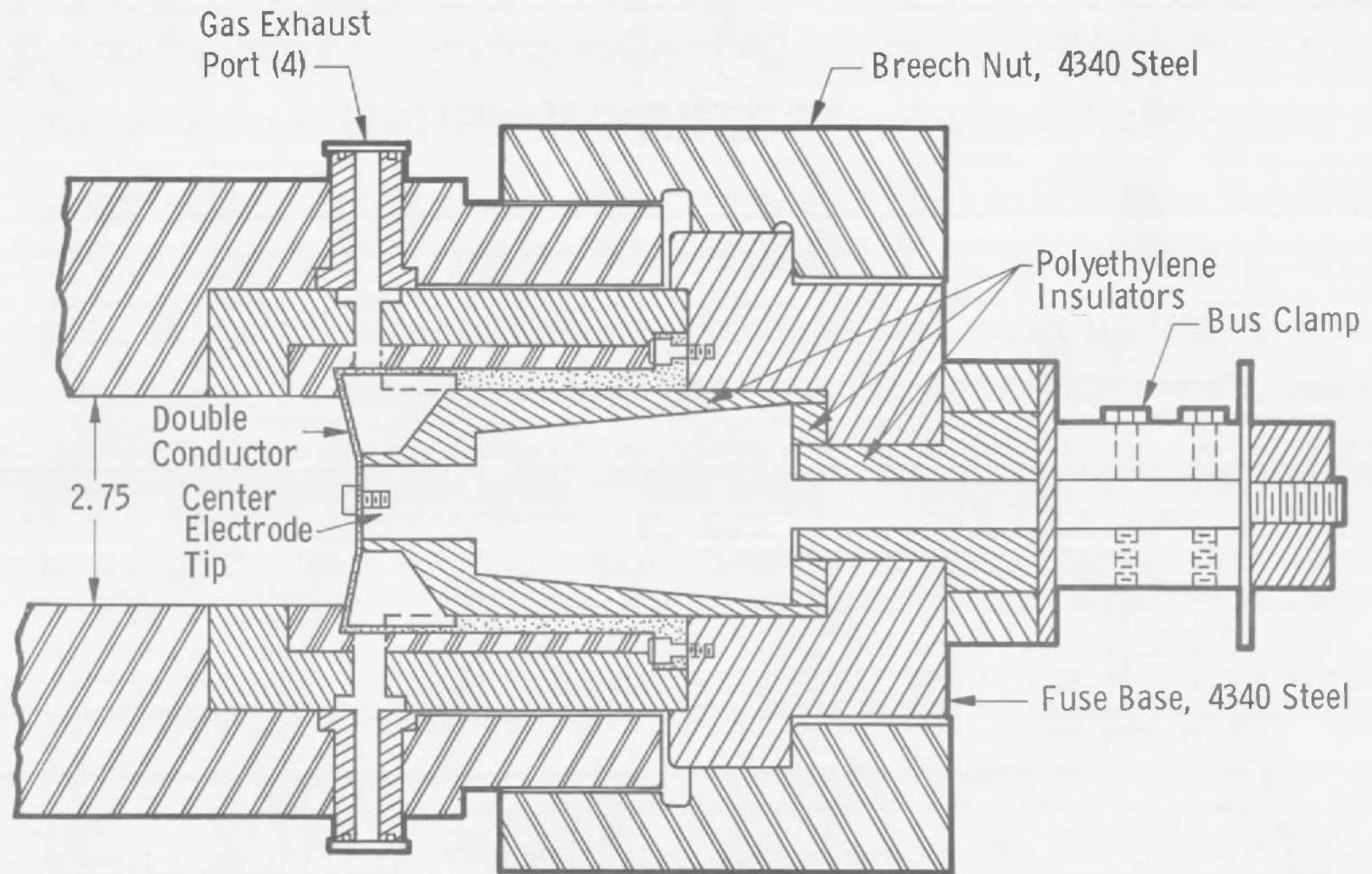


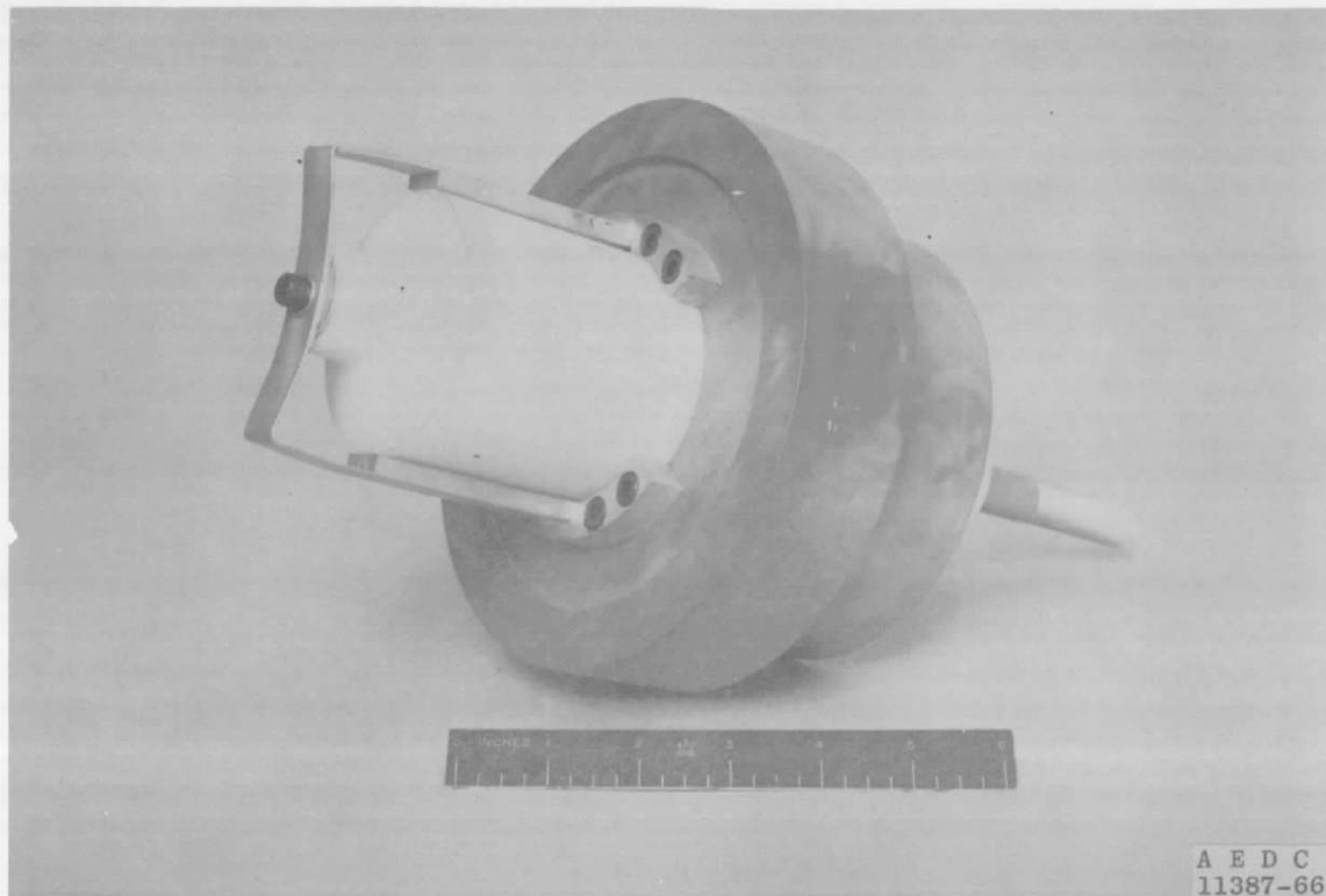
Fig. 13 Typical Data Trace, First Gun Switch Design



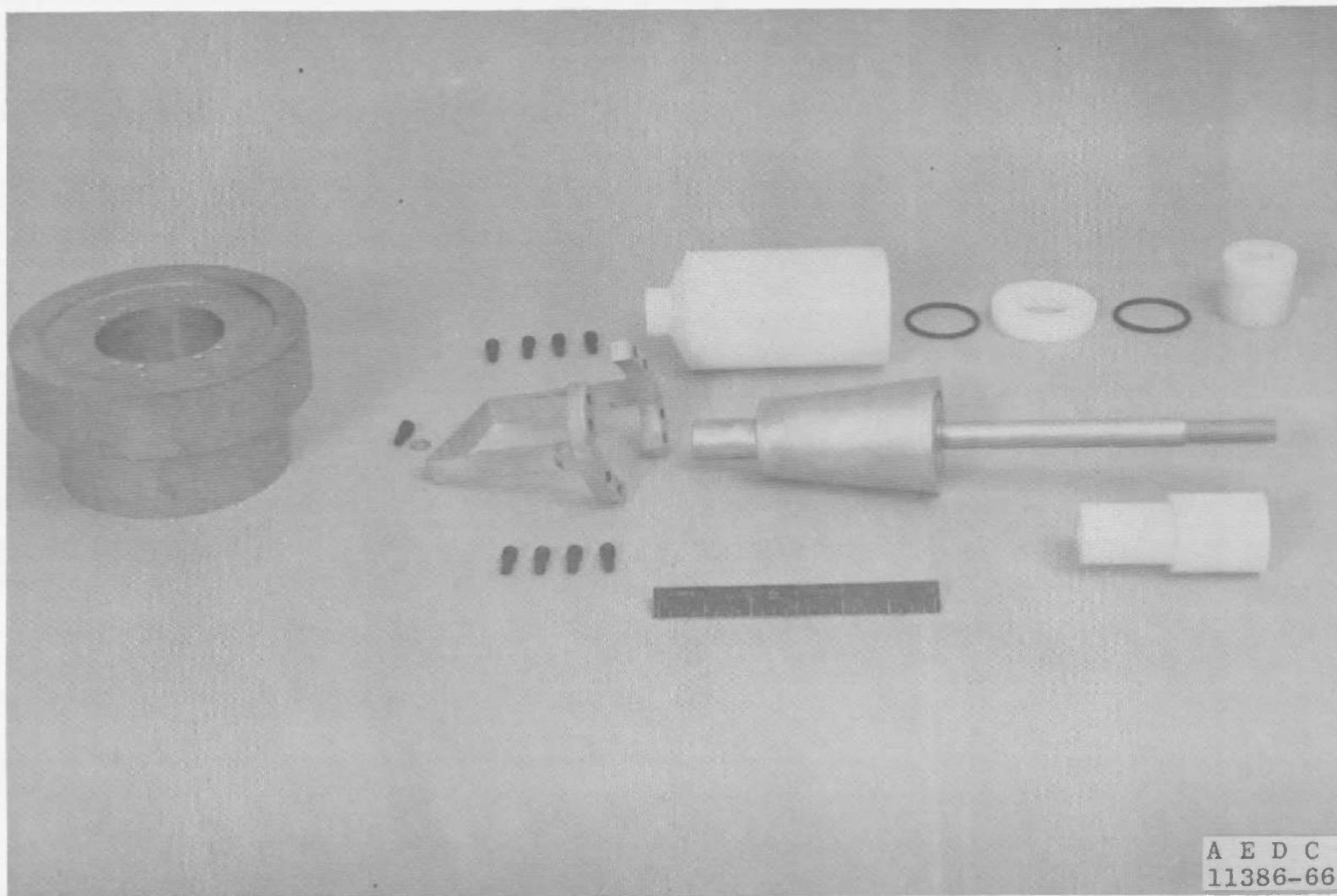
a. Single Conductor
Fig. 14 Final Design Gun Switch



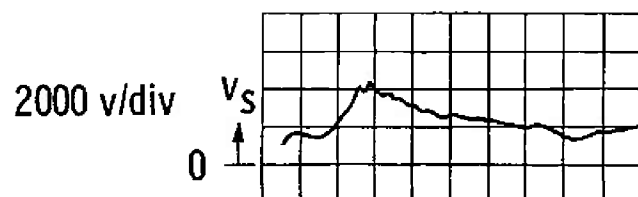
b. Double Conductor
Fig. 14 Continued



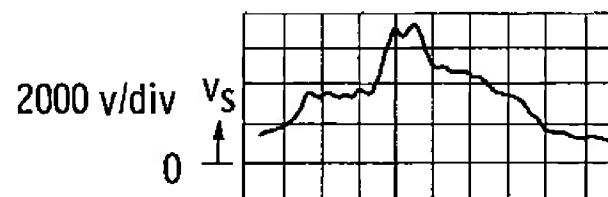
c. Double-Conductor Fuse, Assembled View
Fig. 14 Continued



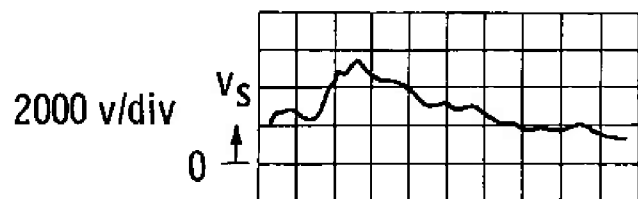
d. Double-Conductor Fuse, Exploded View
Fig. 14 Concluded



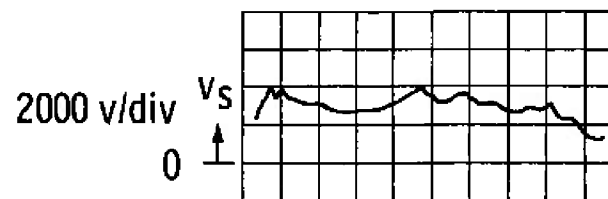
20 μ sec/div $\rightarrow t$
 4-in., 330-gm Piston
 100-gm Powder
 $i_0 = 25,000$ amp



20 μ sec/div $\rightarrow t$
 4-in., 330-gm Piston
 125-gm Powder
 $i_0 = 25,000$ amp



20 μ sec/div $\rightarrow t$
 6-in., 513-gm Piston
 125-gm Powder
 $i_0 = 25,000$ amp



20 μ sec/div $\rightarrow t$
 2.9-in., 229-gm Piston
 125-gm Powder
 $i_0 = 25,000$ amp

Fig. 15 Typical Voltage Traces for Gun Switch (Open-Circuit Condition, Single Conductor)

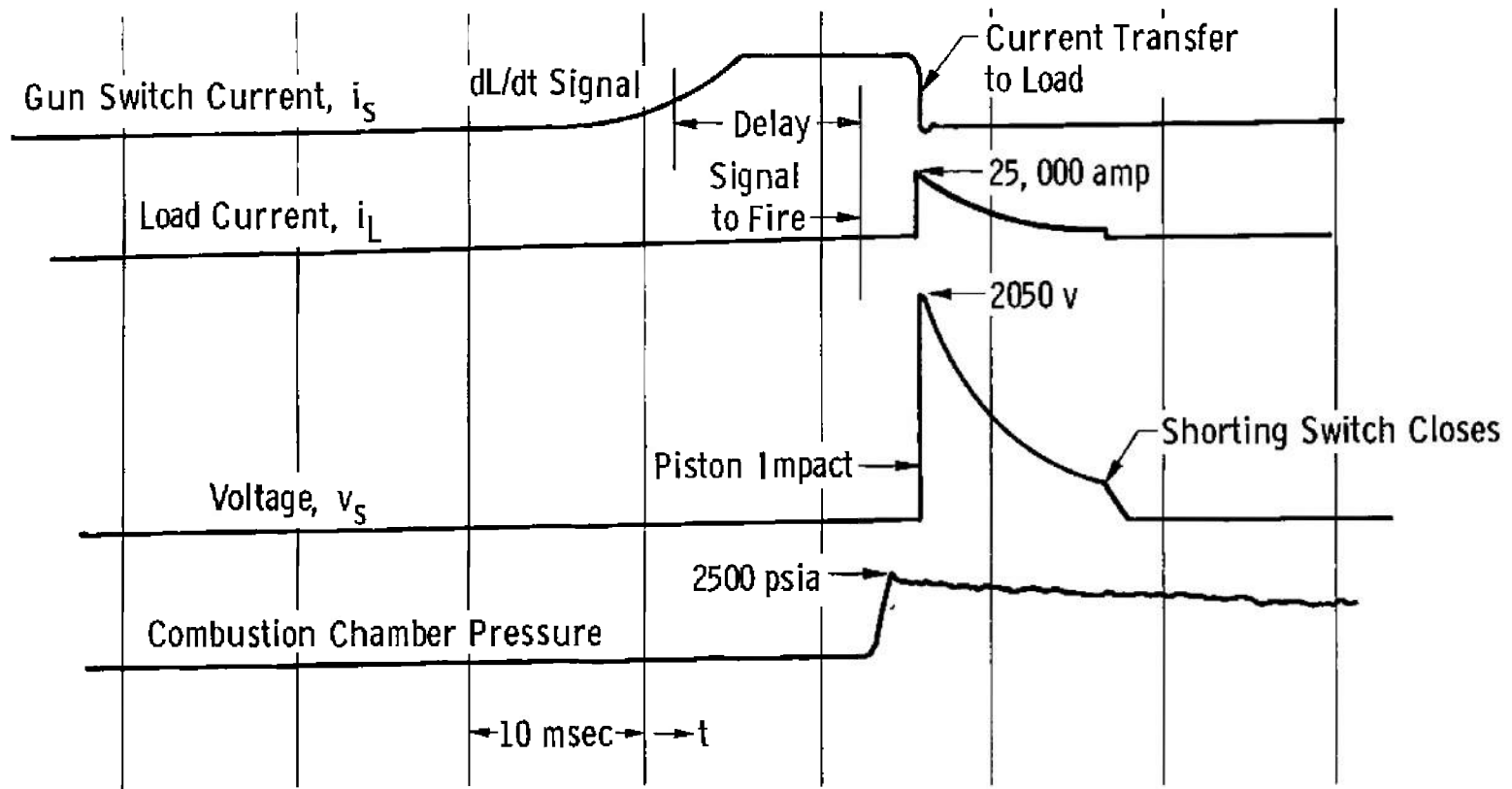
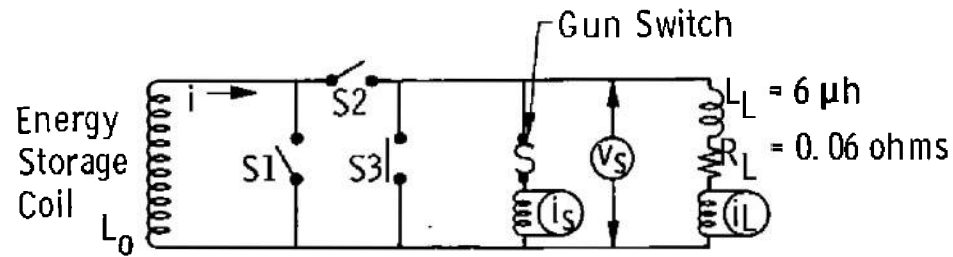
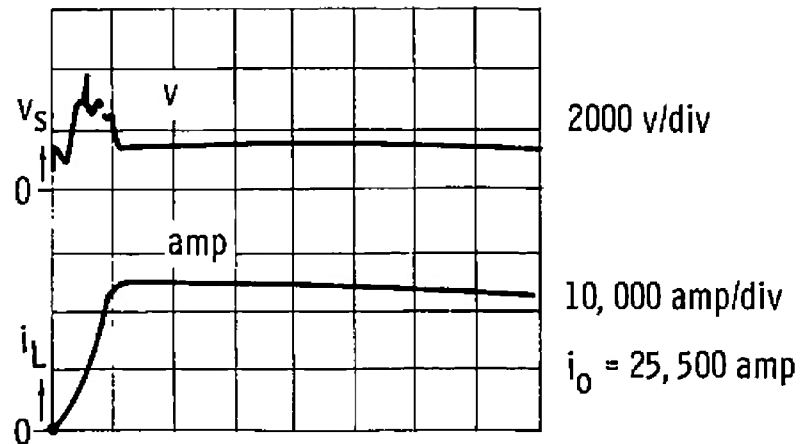
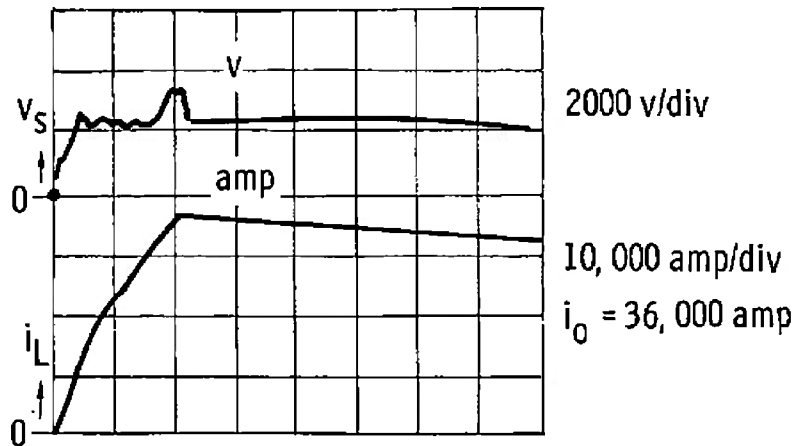


Fig. 16 Typical Data Trace - Final Gun Switch Design

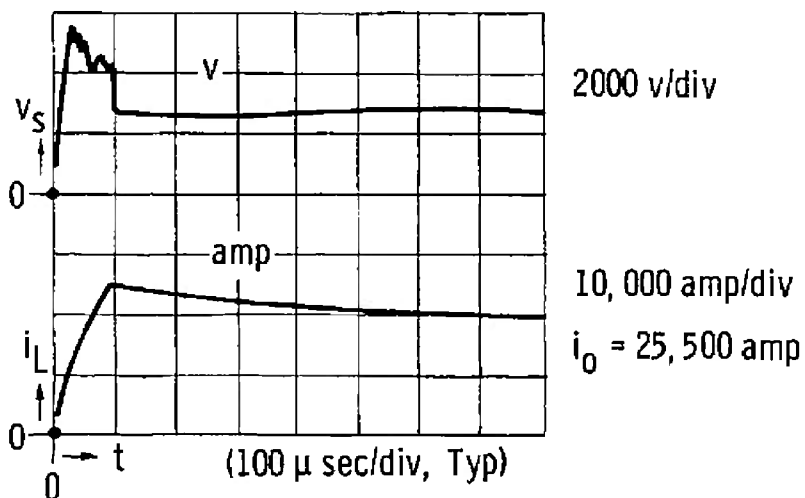
$R_L = 0.06$ ohms
 $L_L = 6 \mu h$
 (Single Conductor)



$R_L = 0.06$ ohms
 $L_L = 6 \mu h$
 (Double Conductor)



$R_i = 0.12$ ohms
 $L_L = 10 \mu h$
 (Double Conductor)

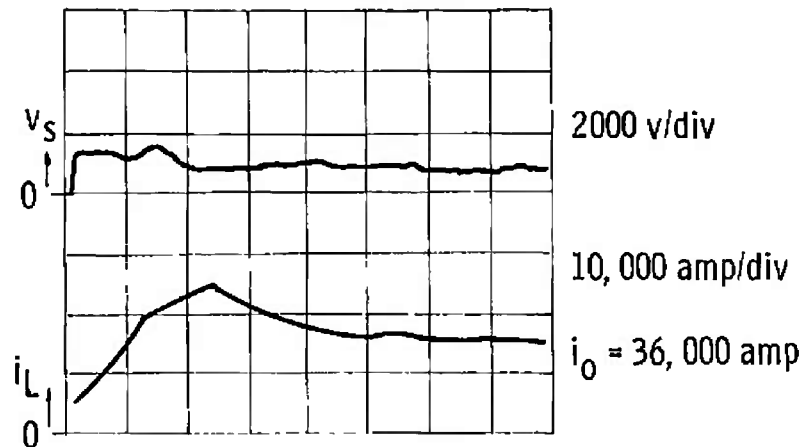


a. Successful Transfers

Fig. 17 Typical Voltage and Current Traces from Gun Switch

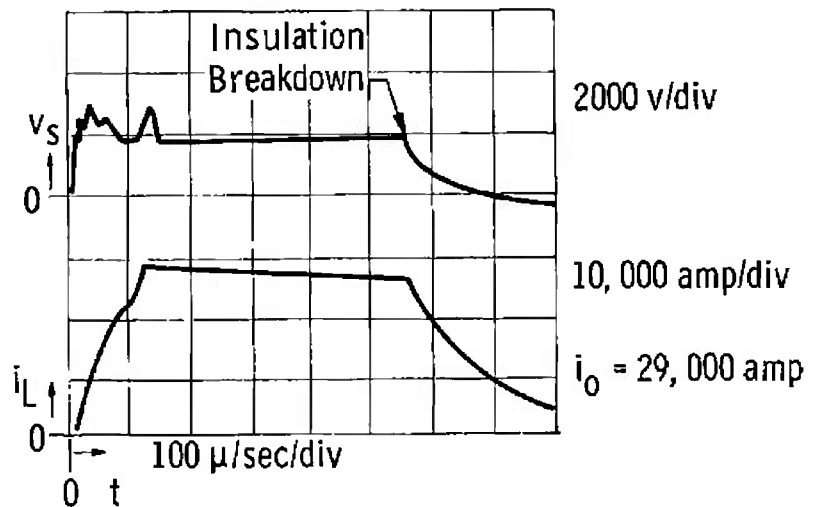
$R_L = 0.06$ ohms
 $L_L = 6 \mu h$
 (Single Conductor)

Partial
 Transfer



$R_L = 0.06$ ohms
 $L_L = 6 \mu h$
 (Double Conductor)

Transfer
 and
 Restrike



b. Malfunctions
 Fig. 17 Concluded

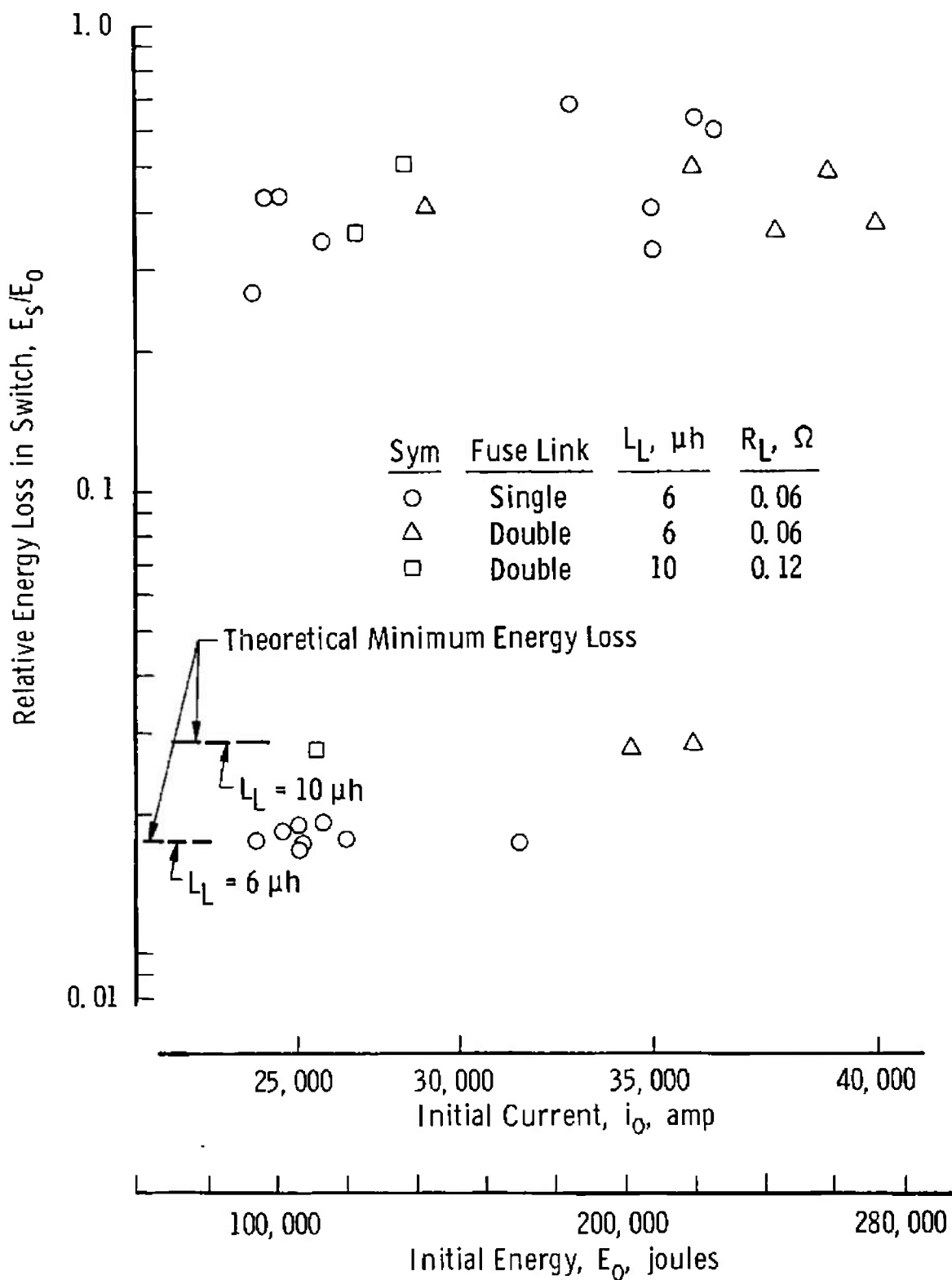


Fig. 18 Gun Switch Energy Loss

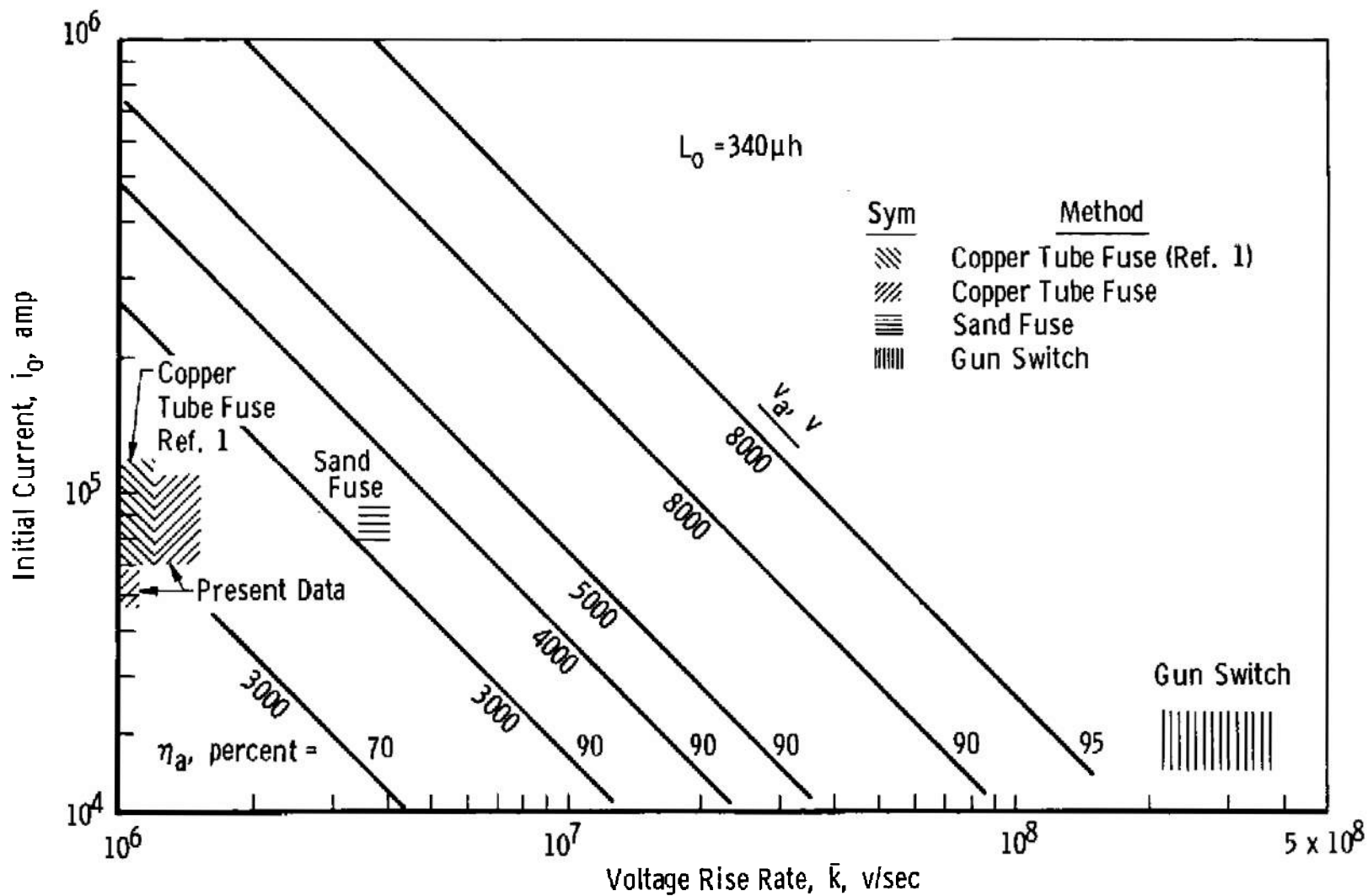


Fig. 19 Comparison of Desired and Experimental Voltage Rise Rates

TABLE I
SHOT CONDITIONS FOR GUN SWITCH

Current, amp	Piston		Gunpowder, gm	Conductor	Parallel Load, ohms	Transfer
	Length, in.	Weight, gm				
24,500	4	330	125	Single	0.06	Yes
24,000	↓	↓	↓	↓	↓	Yes*
23,000	↓	↓	↓	↓	↓	Yes
24,500	↓	↓	↓	↓	↓	Yes*
23,600	↓	↓	100	↓	↓	Yes
25,000	↓	↓	↓	↓	↓	Yes
25,000	↓	↓	↓	↓	↓	No
26,600	↓	↓	↓	↓	↓	Yes
23,500	↓	↓	105	↓	↓	No
25,900	↓	↓	↓	↓	↓	No
25,800	↓	↓	↓	↓	↓	Yes
23,200	↓	↓	↓	↓	↓	Yes
36,500	↓	↓	↓	↓	↓	No
36,000	↓	↓	↓	↓	↓	No
35,000	↓	↓	125	↓	↓	No
33,000	↓	↓	105	↓	↓	No
31,500	6	513	↓	↓	↓	Yes
35,000	↓	↓	↓	↓	↓	No
29,000	4	330	↓	Dual	↓	No
36,000	↓	↓	↓	↓	↓	No
34,500	↓	↓	125	↓	↓	Yes
37,000	↓	↓	↓	Double	↓	No
36,000	↓	↓	↓	↓	↓	Yes
37,500	↓	↓	135	↓	↓	No
40,000	↓	↓	125	↓	↓	No
38,000	↓	↓	130	↓	↓	No
39,000	5	415	130	↓	↓	No
28,500	4	330	105	↓	0.12	No
25,500	↓	↓	↓	↓	↓	Yes
24,000	↓	↓	↓	↓	↓	No
27,000	↓	↓	↓	↓	↓	No

*Insulation failed after transfer had occurred.

TABLE II
TRANSFER EFFICIENCY OF SUCCESSFUL RUNS

Initial Current, i_0 , amp	Stored Energy, E_0 , joules	Energy Consumed by Switch, E_s , joules	Relative Energy Consumed by Switch, E_s/E_0	Experimental Electrical Transfer Efficiency, η , percent
0.06-ohm, 6- μ h Load, Single Fuse				
25,500	102,000	1900	0.0185	\approx 98
25,000	107,000	1800	0.0169	\approx 98
23,600	94,500	1650	0.0175	\approx 98
25,000	107,000	2000	0.0187	\approx 98
26,600	120,000	2130	0.0177	\approx 98
25,800	113,000	2180	0.0191	\approx 98
25,200	108,000	1875	0.0173	\approx 98
31,500	170,000	2940	0.0173	\approx 98
0.06-ohm, 6- μ h Load, Dual Fuse				
34,500	202,000	5600	0.0278	\approx 97
36,000	220,000	6300	0.0285	\approx 97
0.12-ohm, 10- μ h Load, Dual Fuse				
25,500	111,000	3050	0.0275	\approx 97

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11 SUPPLEMENTARY NOTES N/A		12. SPONSORING MILITARY ACTIVITY Army Missile Command Redstone Arsenal, Alabama	
13 ABSTRACT The Arnold Engineering Development Center, von Kármán Gas Dynamics Facility and the Army Missile Command have engaged in a cooperative effort to develop an efficient current interrupting device to be used with inductive power supplies. A unique switch, termed the "gun switch", has been developed which utilizes gunpowder as a propellant to drive a plastic piston into, and shear, an electrical ribbon conductor. The gun switch has transferred up to 220,000 joules (36,000 amp) into an 0.06-ohm, 6- μ h load with an electrical transfer efficiency of 97 percent.			

KEY WORDS

switching circuits
inductive power supplies
gunpowder propellants
gun switches
electrical ribbon conductors
transfer efficiencies

LINK A

ROLE

WT

LINK B

ROLE

WT

LINK C

ROLE

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